Theoretical Interpretation of Forward Neutron A_N

RIKEN/RBRC
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PP A_N

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Single transverse spin asymmetry of forward neutrons

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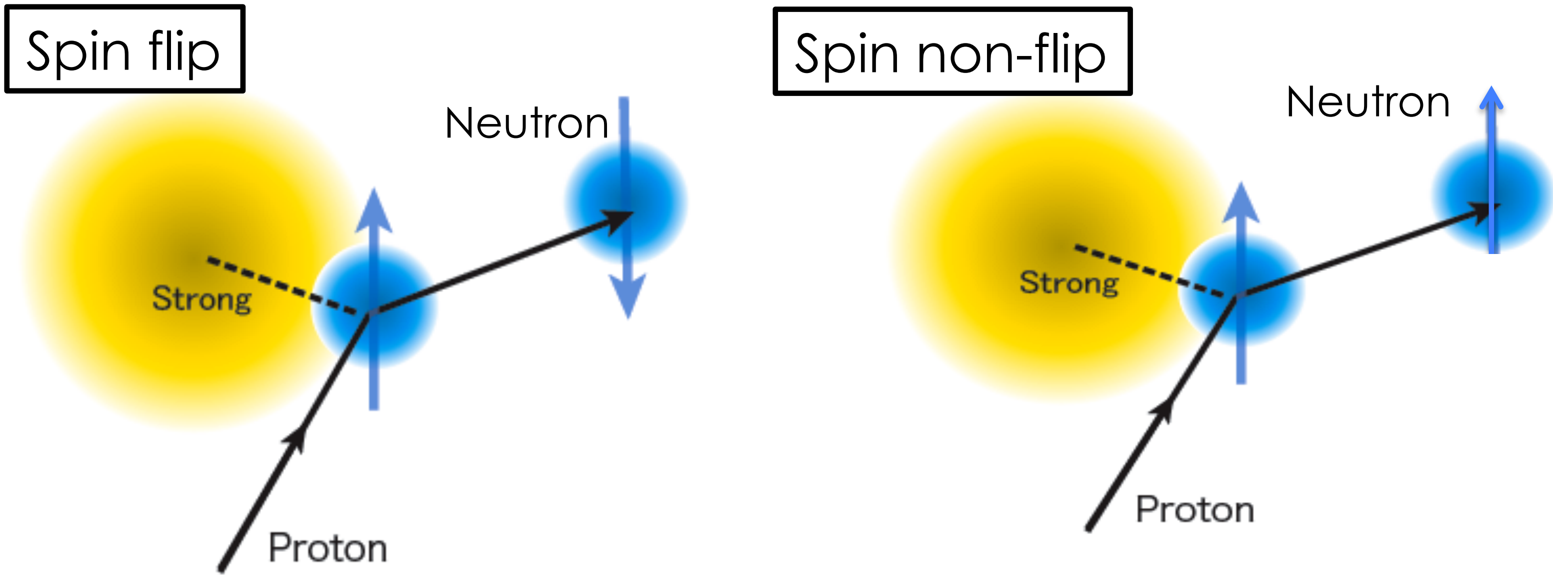
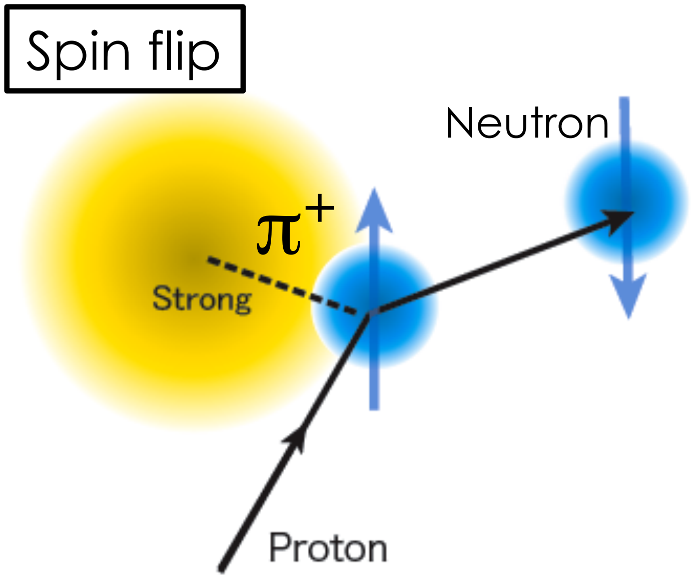
We calculate the single transverse spin asymmetry $A_N(t)$, for inclusive neutron production in pp collisions at forward rapidities relative to the polarized proton in the energy range of RHIC. Absorptive corrections to the pion pole generate a relative phase between the spin-flip and nonflip amplitudes, leading to a transverse spin asymmetry which is found to be far too small to explain the magnitude of A_N observed in the PHENIX experiment. A larger contribution, which does not vanish at high energies, comes from the interference of pion and a_1-Reggeon exchanges. The unnatural parity of a_1 guarantees a substantial phase shift, although the magnitude is strongly suppressed by the smallness of diffractive $\pi p \to a_1 p$ cross section. We replace the Regge a_1 pole by the Regge cut corresponding to the $\pi\rho$ exchange in the 1^+S state. The production of such a state, which we treat as an effective pole a, forms a narrow peak in the 3π invariant mass distribution in diffractive πp interactions. The cross section is large, so one can assume that this state saturates the spectral function of the axial current and we can determine its coupling to nucleons via the partially conserved axial-vector-current constraint Goldberger-Treiman relation and the second Weinberg sum rule. The numerical results of the parameter-free calculation of A_N are in excellent agreement with the PHENIX data.

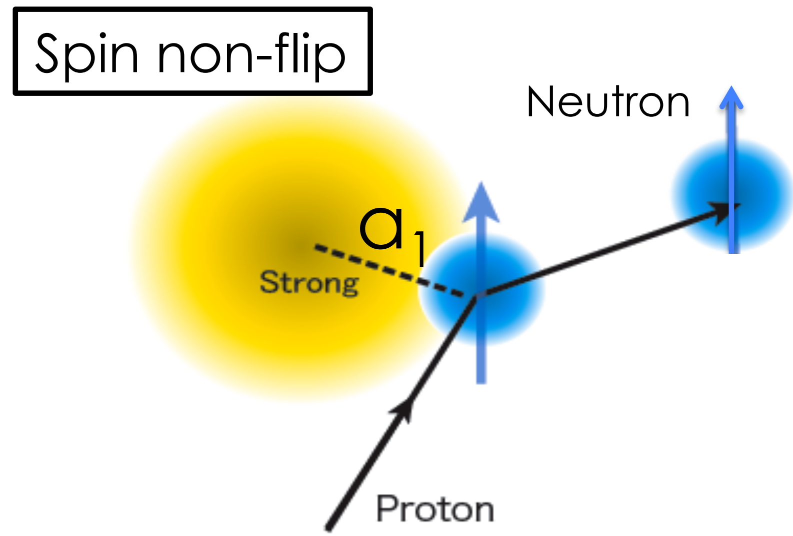
$p^{\uparrow}p$ Forward Neutron A_N

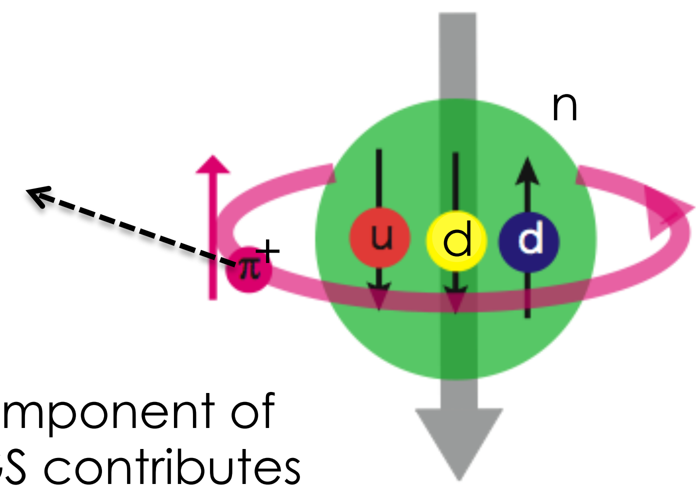


$$A_N \approx \frac{\phi^*_{non-flip}\phi_{flip}\delta}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2}$$

$p^{\uparrow}p$ Forward Neutron A_N



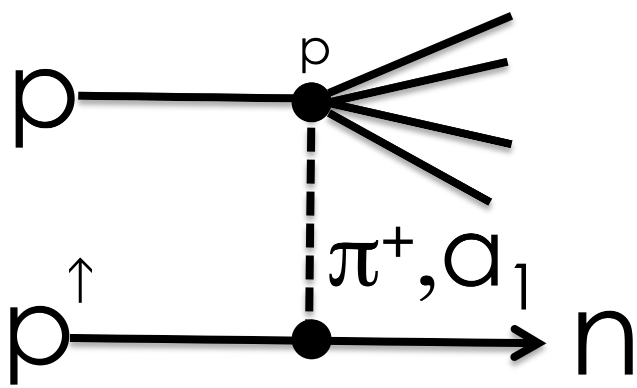




a_1 Reggeon
Spin Parity = 1^+

n + π^+ component of
proton GS contributes

$p^{\uparrow}p$ Forward Neutron A_N



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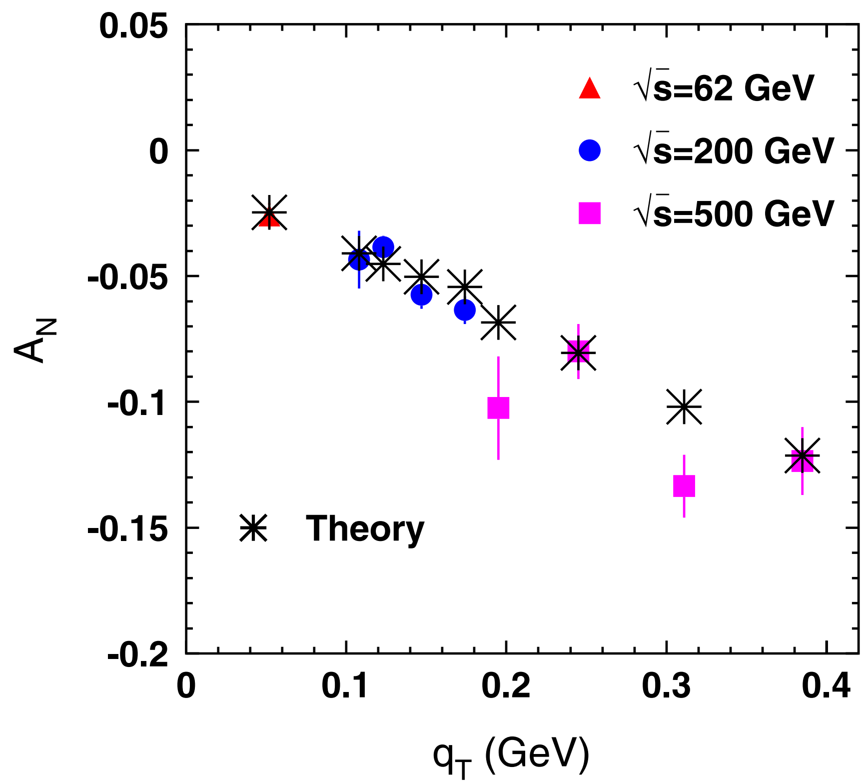
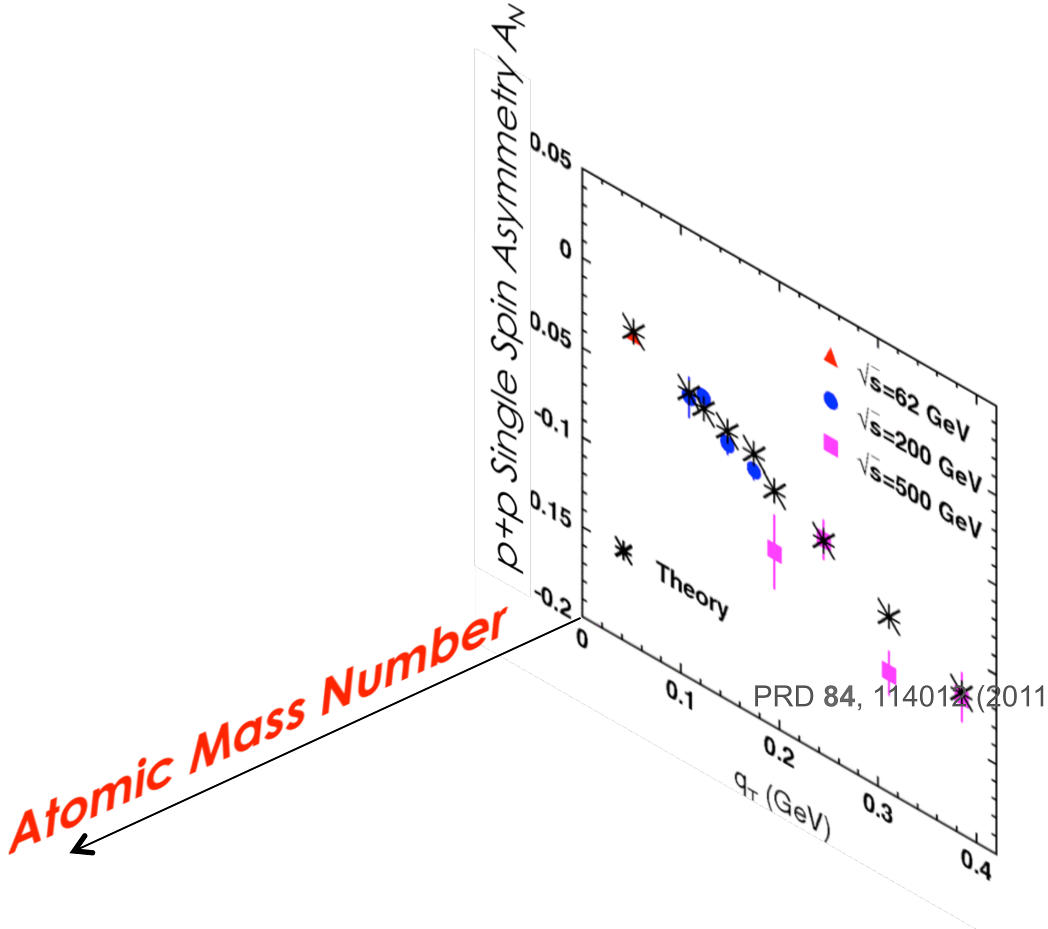
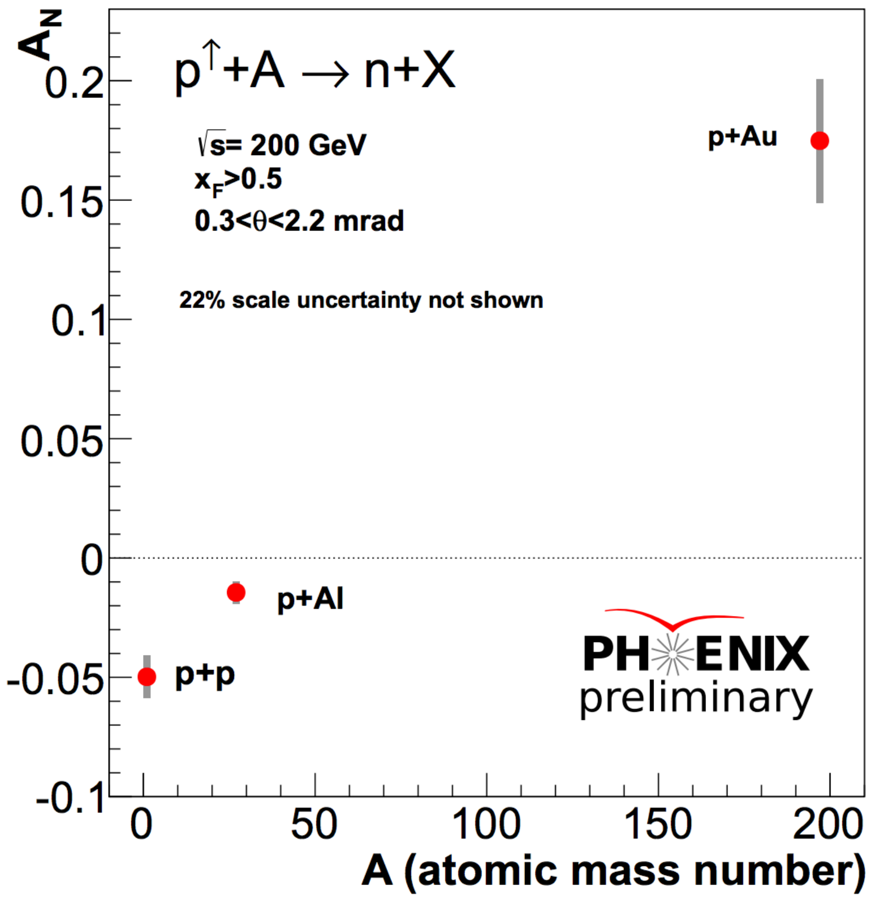


Well explained by the interference between π and a_1 Reggion

ATOMIC MASS DEPENDENCE



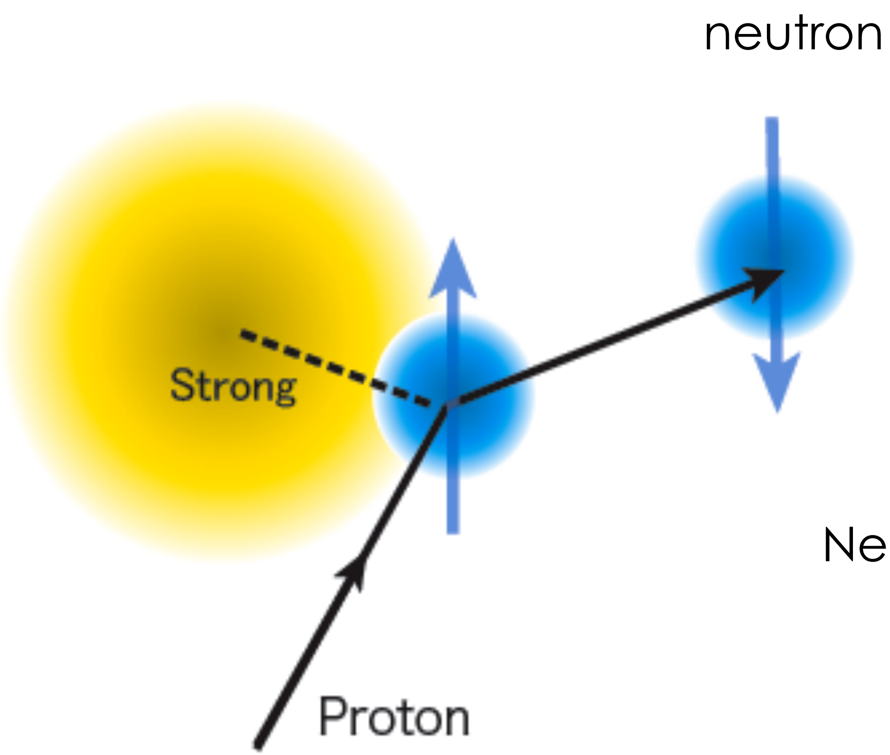
Atomic Mass Number Dependence



	# of proton	# of neutron
p	1	0
Al	13	14
Au	79	118

- Isospin Symmetry
- Surface Structure of Nucleus
- QED Process
- Gluon Saturation
- else

Surface Effect of Nucleus



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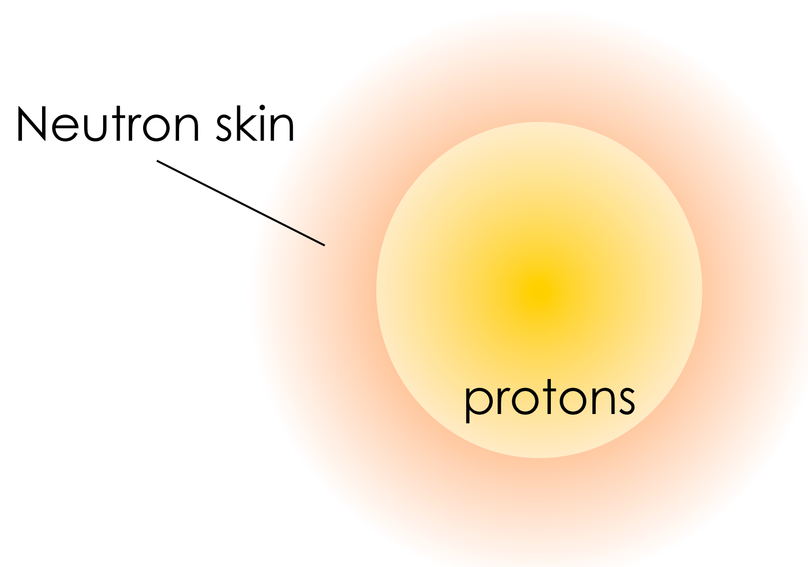
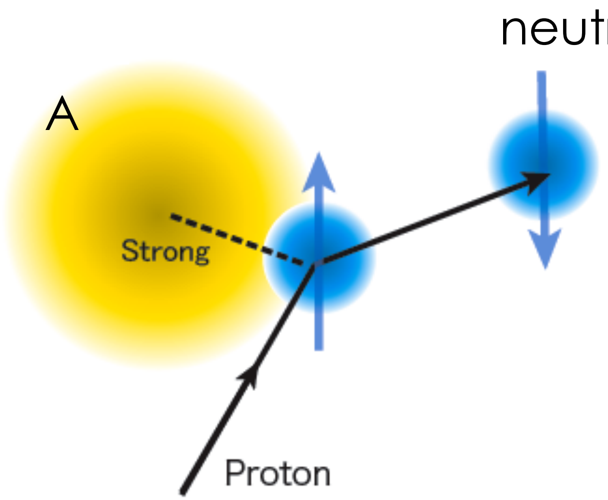
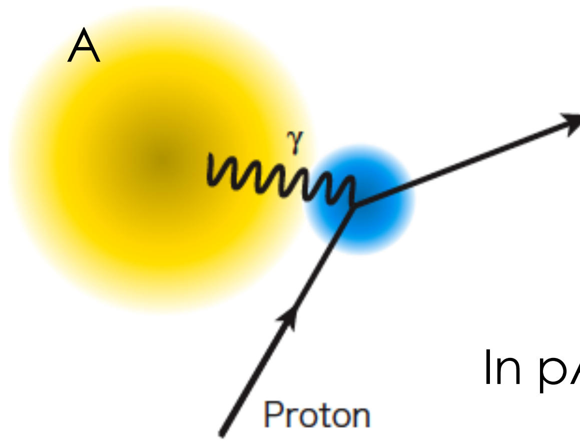


QED Process
Ultra Peripheral Collision (UPC)

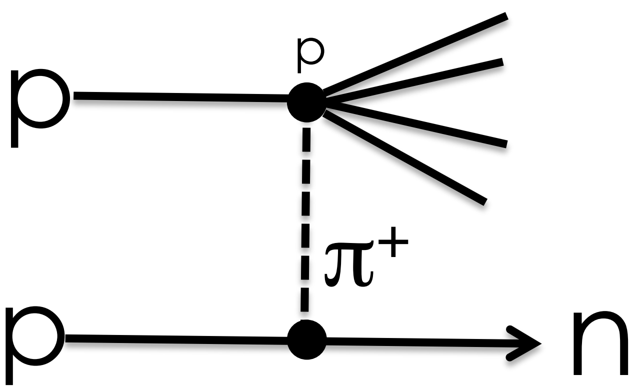


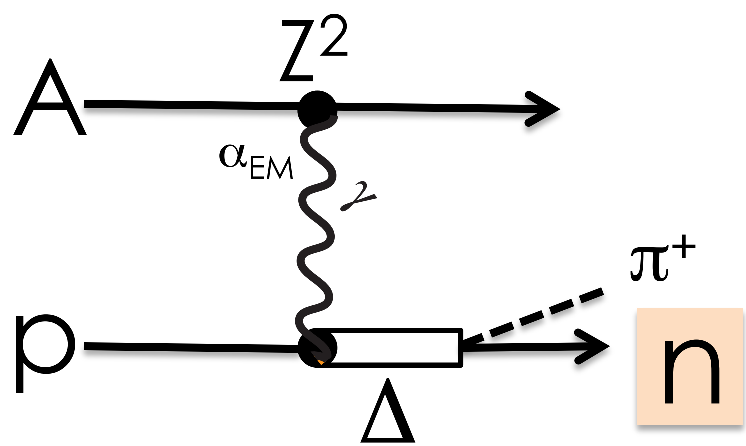


$t \rightarrow 0$

In pAu case

$$Z^2 \bullet \alpha_{EM} \sim 79^2/137 \sim 45$$

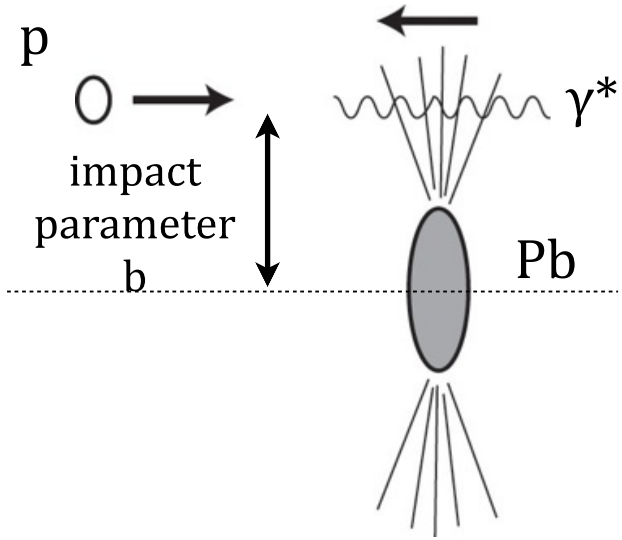




Ultra Peripheral Collision

UPC

Event Generation of UPCs



Event Generation of UPCs

=

Flux of quasi photons

×

Cross section of p-γ

×

Event Generation of p-γ

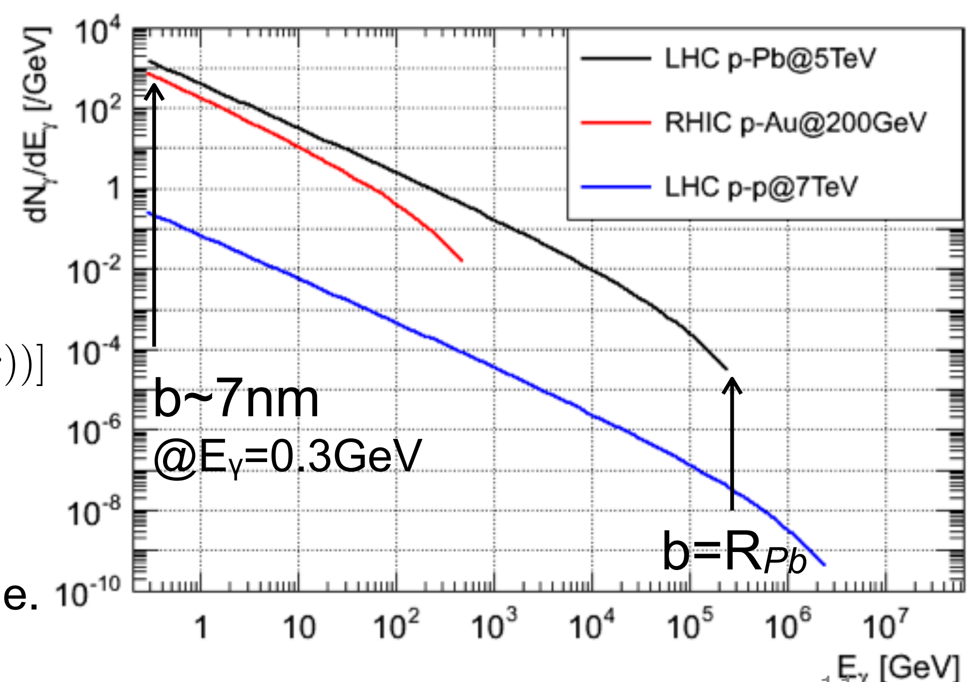
Flux of quasi photons

Weizsacker-Williams method

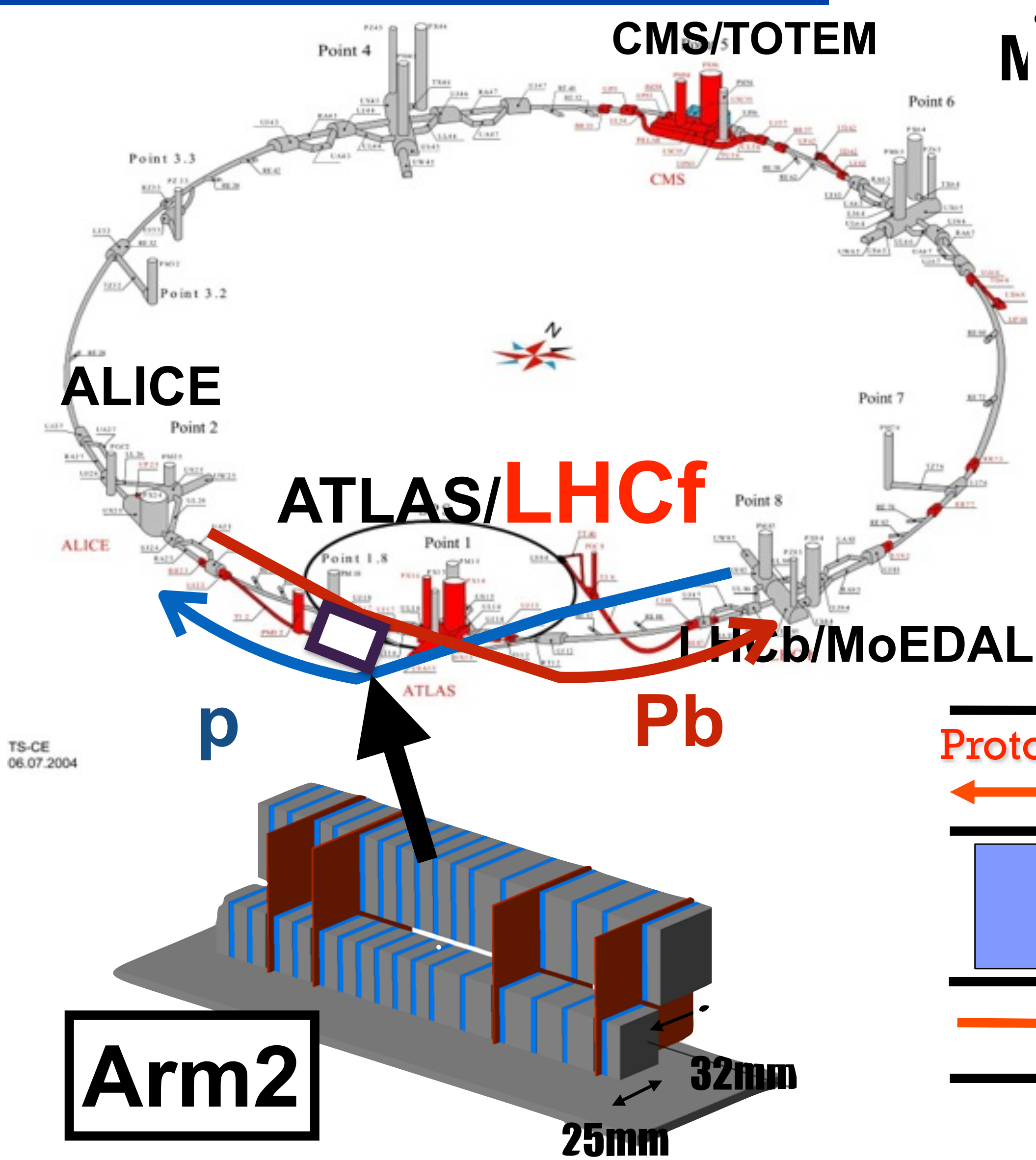
$$\frac{dN_{\gamma*}}{dE_{\gamma*}} = \frac{2Z^2\alpha}{\pi E_{\gamma*}}[xK_0(x)K_1(x) + \frac{x^2}{2}(K_0^2(x) - K_1^2(x))]$$

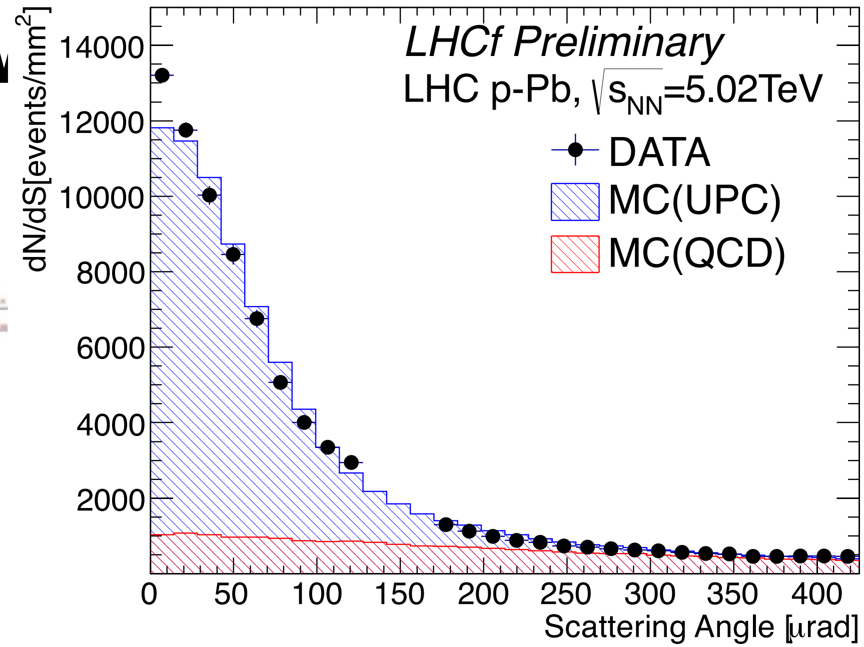
$$\simeq \frac{2Z^2\alpha}{\pi E_{\gamma*}}(log\frac{1.123}{x} - 1) \qquad (if\ E_{\gamma*} << E_{max})$$

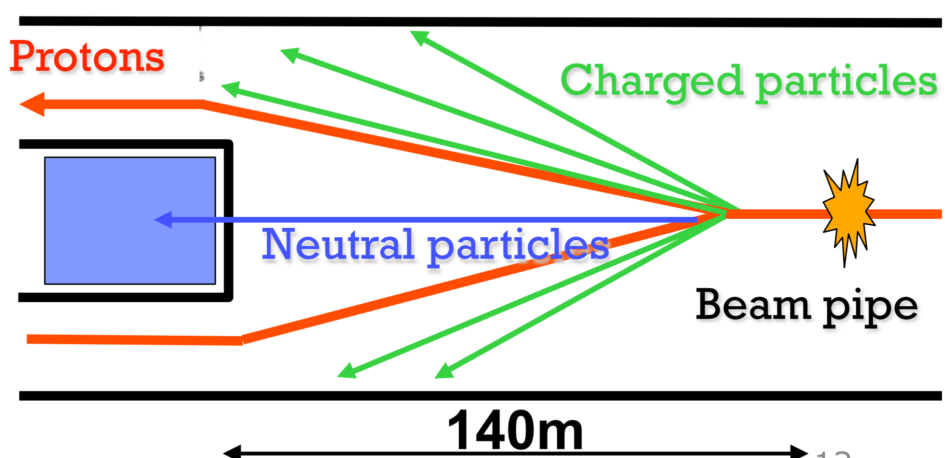
$E_{\gamma*}$: energy of photons at the proton rest frame.



The LHCf experiment







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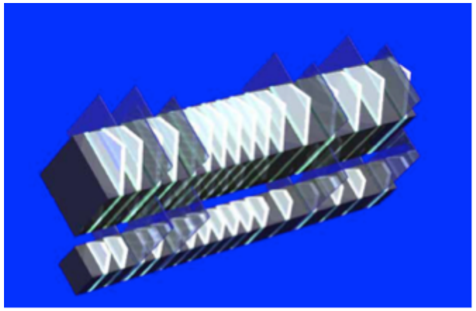
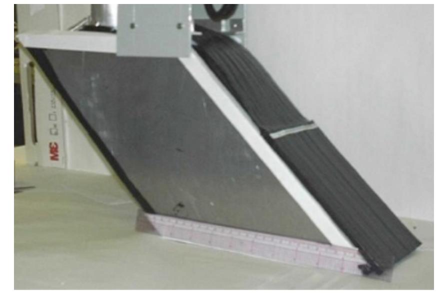
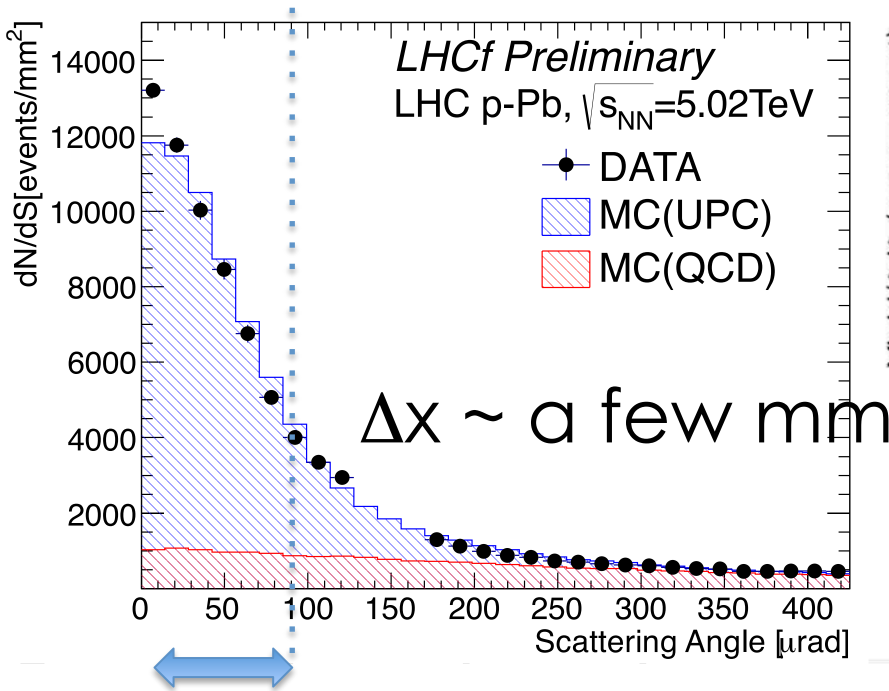
Forward Neutron Angular Distributions

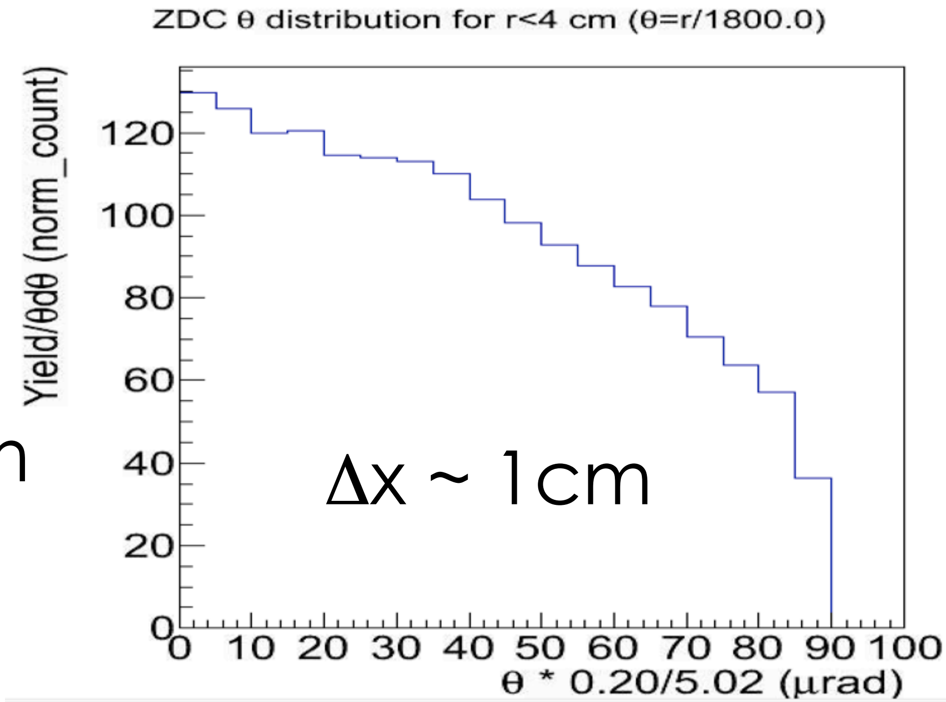
LHCf



PHENIX ZDC







The ZDC acceptance doesn’t reach QCD dominant region.

Forward hadron production in ultra-peripheral proton–heavy-ion collisions at the LHC and RHIC

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October 6, 2015

Abstract We present a study of hadron production in the forward rapidity region in ultra-peripheral proton–lead ($p+$ Pb) collisions at the LHC and proton–gold ($p+$ Au) collisions at RHIC. The present paper is based on the Monte Carlo simulations of the interactions of a virtual photon emitted by a fast moving nucleus with a proton beam. The simulation consists of two stages: the STARLIGHT event generator for the simulation of the virtual photon flux, which is coupled to the SOPHIA, DPMJET, and PYTHIA event genera-

overlap between the colliding hadrons. Therefore, hadronic interactions are strongly suppressed. Nevertheless, virtual photons emitted from one of the two colliding hadrons may interact with another hadron. This process is usually referred as ultra-peripheral collision (UPC, see Ref. [1,2] for a review).

The use of UPCs has so far been addressed in the determination of the gluon distribution in protons and nuclei. For example, photoproduction of quarkonium in ultra-peripheral

UPC : SOPHIA

2.2 Simulation of low-energy photon–proton interaction

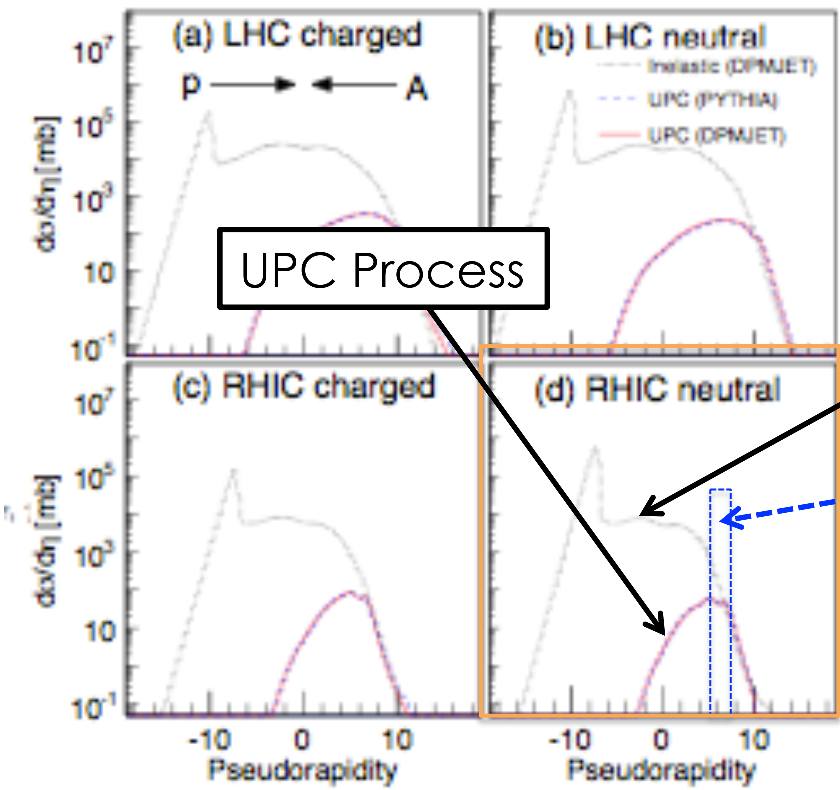
The particle production by the interaction of a low-energy photon with a proton is simulated by the SOPHIA 2.1 event generator [11]. In SOPHIA, particle production via baryon resonances, direct pion production, and multiparticle production are taken into account. For the baryon resonances, the known resonances from $\Delta(1232)$ to $\Delta(1950)$ are considered with their physical parameters. The resonance decay is supposed to occur isotropically according to the phase

QCD : DPMJET

2.4 Simulation of hadronic interaction

In the study of this paper, the DPMJET generator is used for the MC simulation of hadronic interactions, which include non-diffractive and diffractive interactions but do not include elastic scattering. The multiple scattering process in the interaction with a nuclear target, which causes nuclear

Rapidity Distributions by MC



QCD Process

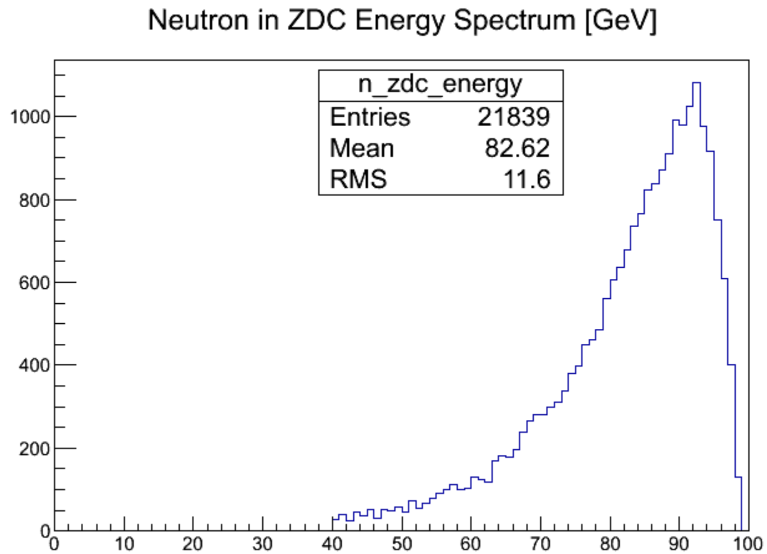
Minjung's cut@ZDC

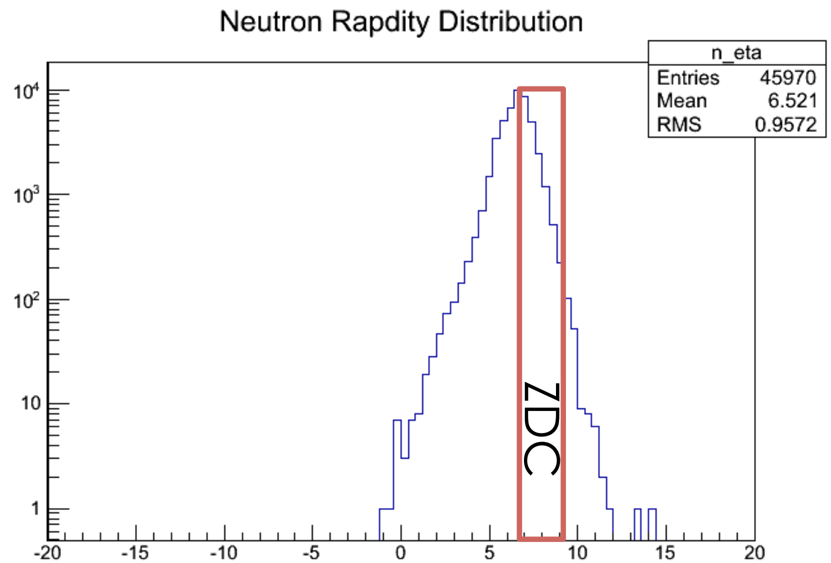
6.8 < ZDC acceptance < 8.2

Fig. 1 Charged (left) and neutral particle (right) pseudorapidity distributions at the LHC (top) and RHIC (bottom), respectively. The solid curves and dashed curves indicate the UPC simulation events generated by using STARLIGHT+SOPHIA+DPMJET and STARLIGHT+SOPHIA+PYTHIA, respectively. The dotted curves indicate the simulated $p+Pb$ and $p+Au$ inelastic events with DPMJET at the LHC and RHIC, respectively. The directions of the moving proton (p) and the nucleus (A) are indicated by arrows in the upper left panel.

Neutral particle yields are in the similar order between QCD and UPC

UPC Neutron Raw Spectrum





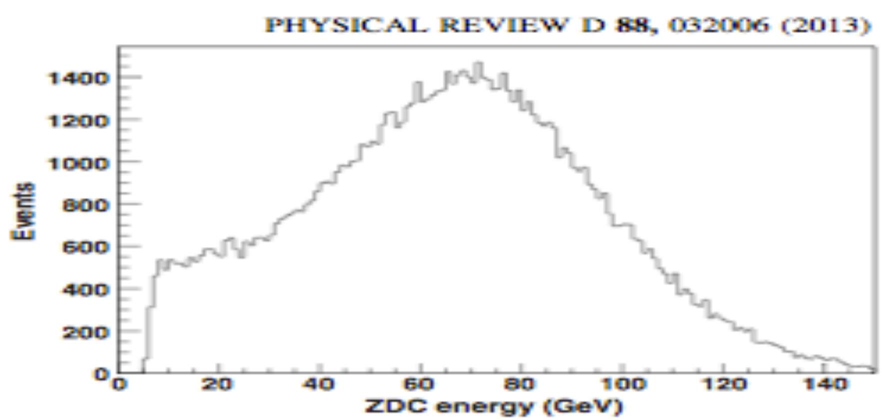
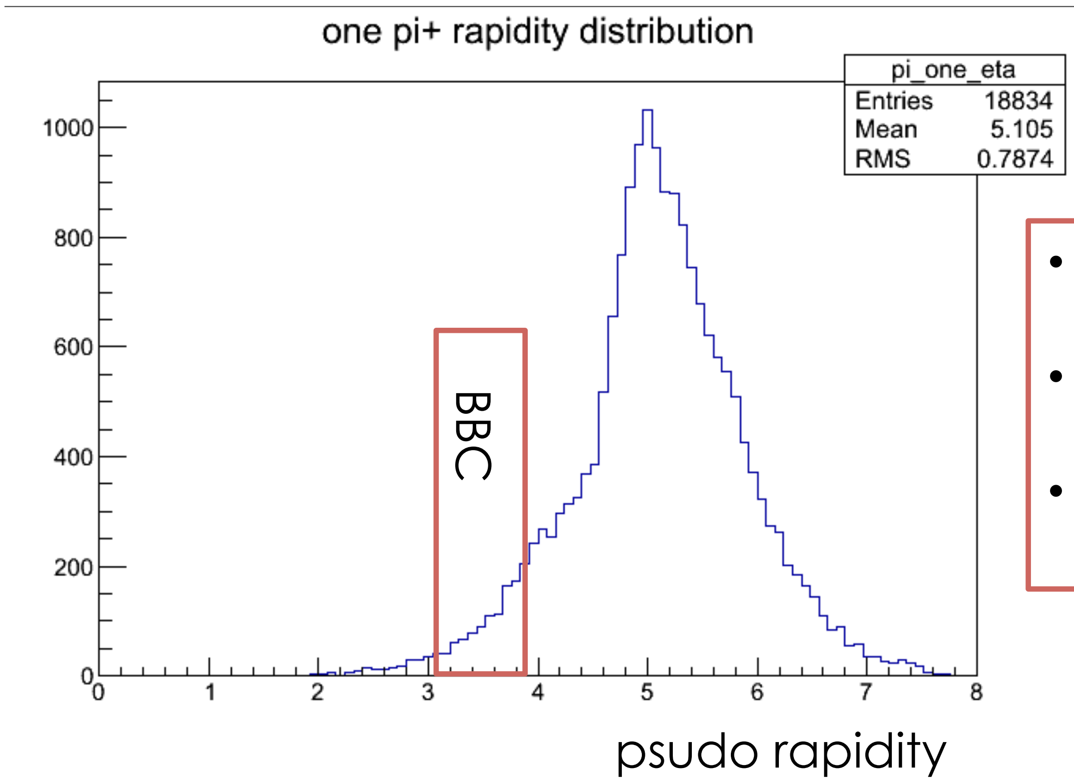
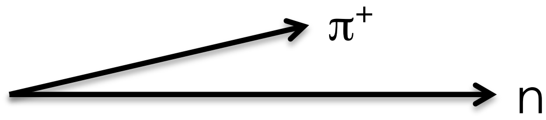


FIG. 10. The energy distribution measured with the ZDC after the neutron identification and the acceptance cut ($r < 2$ cm, corresponds to $p_T < 0.11 \cdot x_F$ GeV/c).

- Energy profile is biased towards higher energy side than QCD one as Boris predicted.
- Rapidity distribution looks skinner than Gaku's draft.

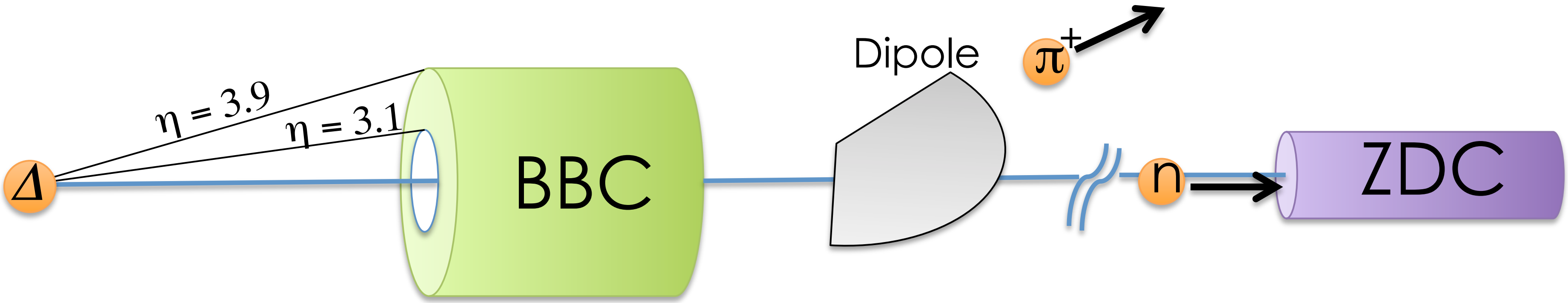
UPC π^+ (β>0.7) kinematics





- Most of UPC events decay into two bodies (n+π^+ from Δ)
- Very little make it to BBC acceptance.
- Most of pions will escaped through BBC hole.

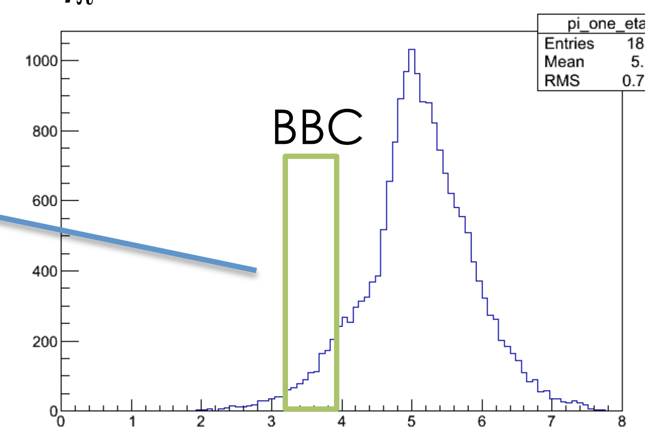
Can we identify UPC events?



Most of decayed pions go through BBC hole and will be swept away by the dipole magnet (DX).

Very little coincidence measurements of final state from resonance.

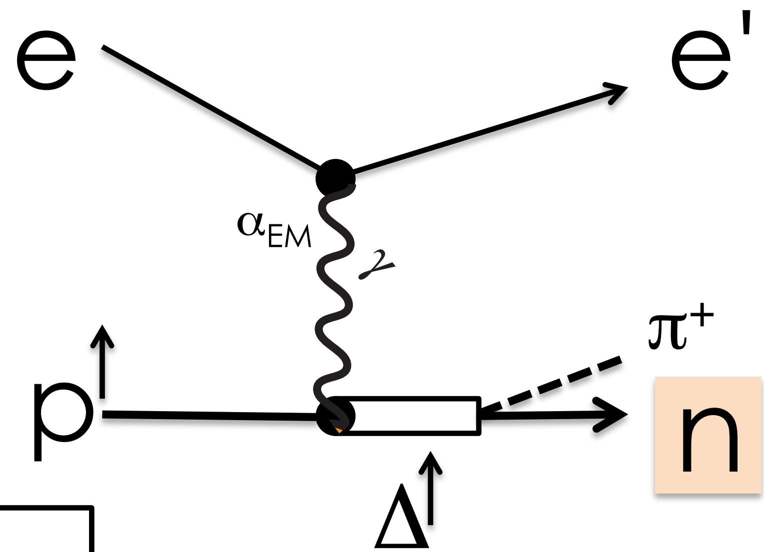
η_π distribution of n+π^+ events



π^+ Rapidity

Simulation by Gaku Mitsuka

Asymmetry Induced by Δ



Transversely polarized fixed proton target

Polarized Delta

Asymmetric neutron decay from polarized Δ

So far, I haven't heard such an experiments in electron facilities

UPC Summary

- LHCf claims there is distinctively large forward neutron production near zero degree in p-Pb
- Neutrons are mostly decayed from Δ excitation of forward going proton
- About ½ of photon yields of LHCf is expected in RHIC p-Au.
- Majority of decayed counterpart π flies through BBC beam hole (undetected).
- Don't aware of experimental evidence of large A_N induced by UPC alone.

Full Description

$$A_N \approx \phi^*_{flip}\phi_{non-flip}$$

$$\phi_{flip} = \phi^{EM}_{flip} + \phi^{had}_{flip}$$

$$\phi_{non-flip} = \phi^{EM}_{non=flip} + \phi^{had}_{non-flip}$$

δ : relative phase of amplitudes

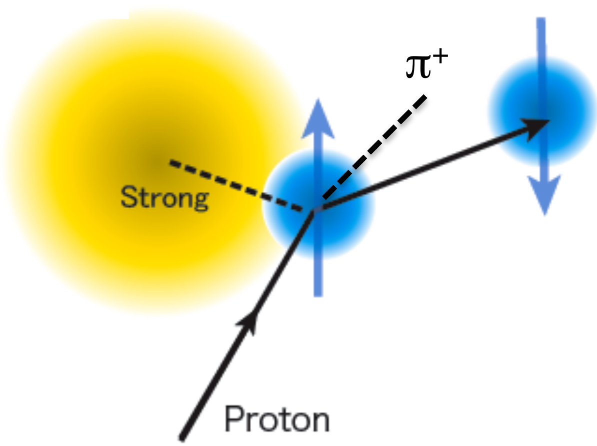
$$A_N \approx \left(\phi^{EM*}_{flip} + \phi^{had*}_{flip}\right)\left(\phi^{EM}_{non=flip} + \phi^{had}_{non-flip}\right)$$

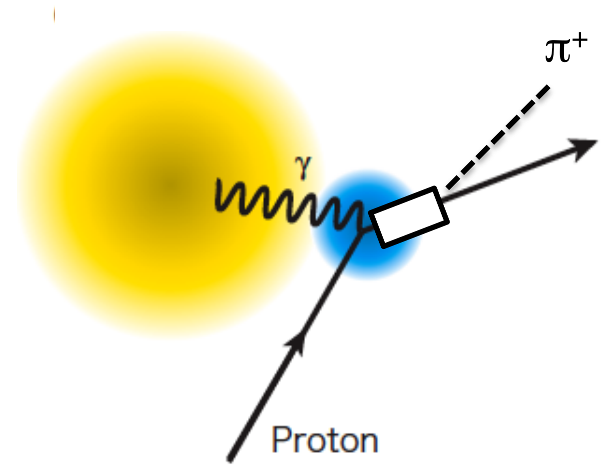
$$= \underbrace{\phi^{EM*}_{flip}\phi^{had}_{non-flip}\delta + \phi^{had*}_{flip}\phi^{EM}_{non=flip}\delta}_{\text{Elastic (polarimeter)}} + \phi^{EM*}_{flip}\phi^{EM}_{non=flip}\delta + \phi^{had*}_{flip}\phi^{had}_{non-flip}\delta$$

For pp:

$$A_N \approx \phi^{had*}_{flip}\phi^{had}_{non-flip}\delta \qquad \phi^{EM} \rightarrow 0$$

Coulomb-Nuclear Interference(CNI)





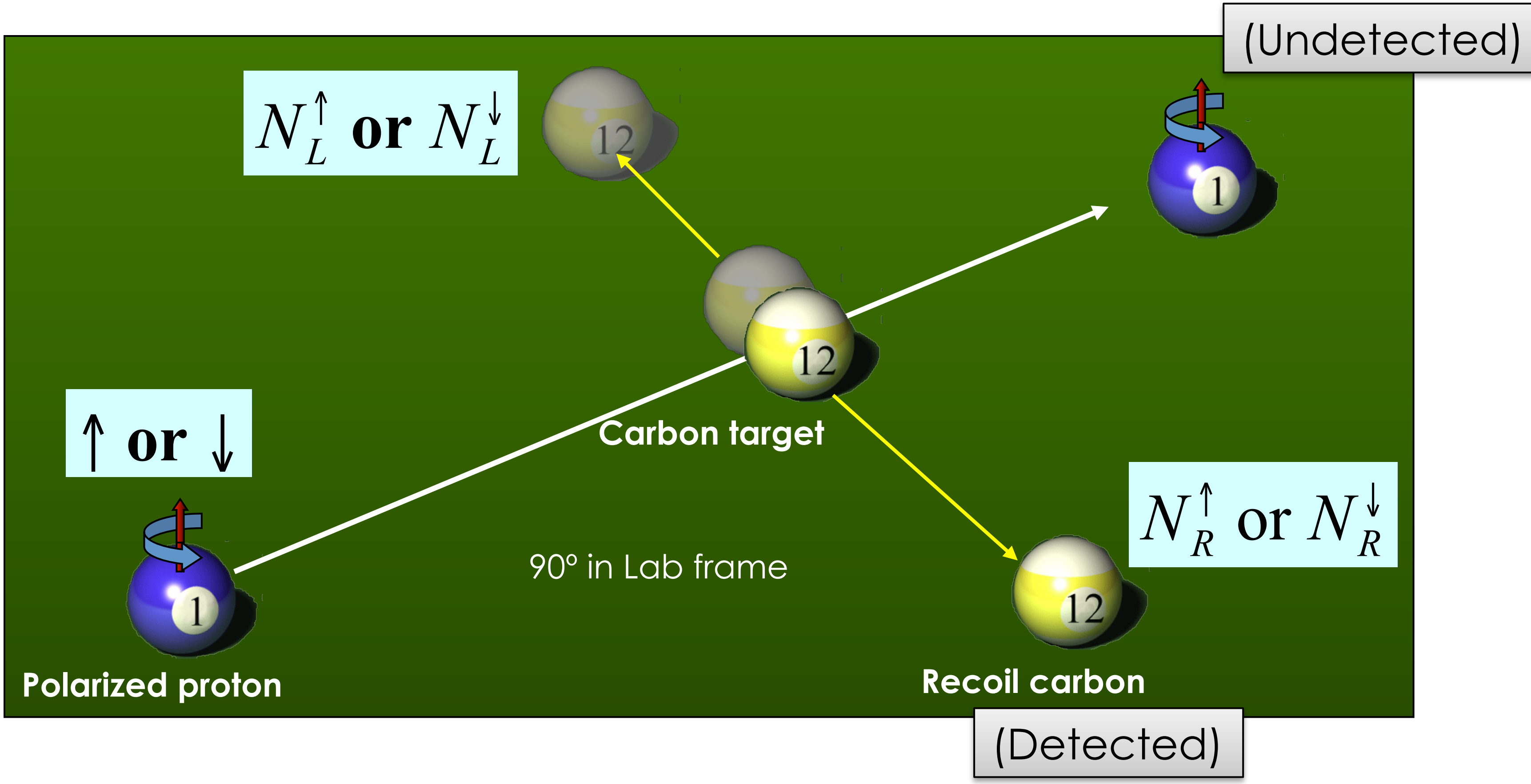
$t \rightarrow 0$

$$A_N = \phi_{flip}^{EM*}\phi_{non-flip}^{had}\delta + \phi_{flip}^{had*}\phi_{non=flip}^{EM}\delta + \phi_{flip}^{EM*}\phi_{non=flip}^{EM}\delta + \phi_{flip}^{had*}\phi_{non-flip}^{had}\delta$$

More terms to be considered. Possibly leads to large asymmetry.
Each EM amplitude would be proportional to Z.

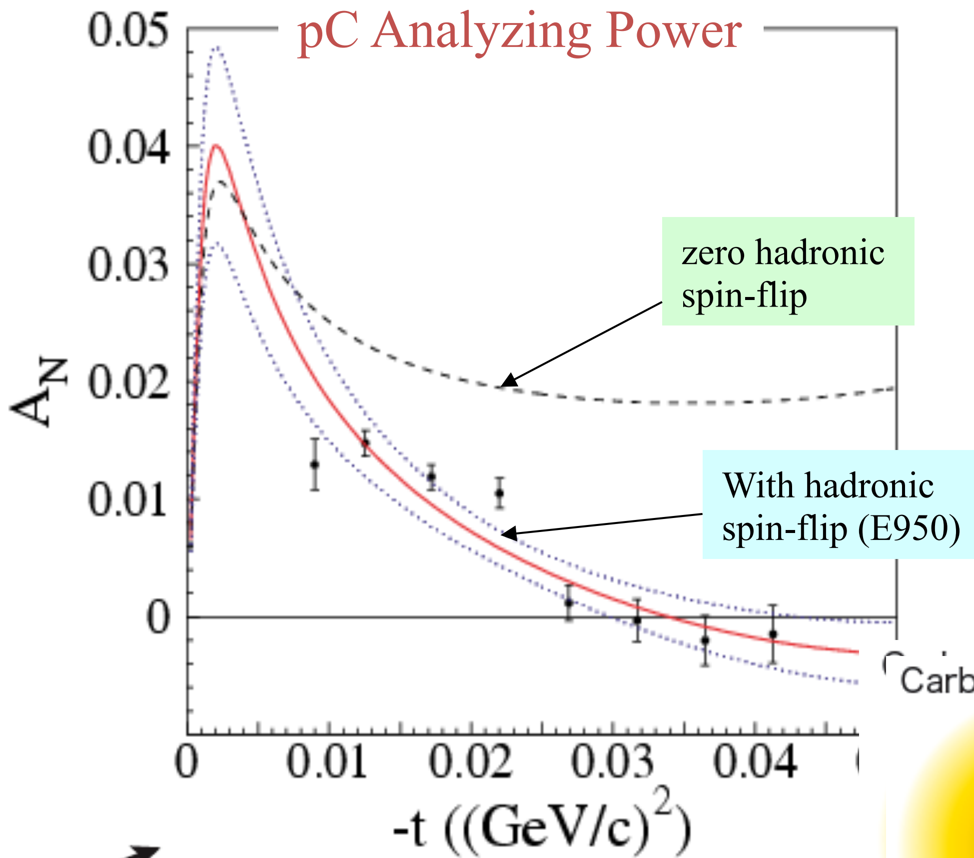
CNI

RHIC CNI Polarimeter

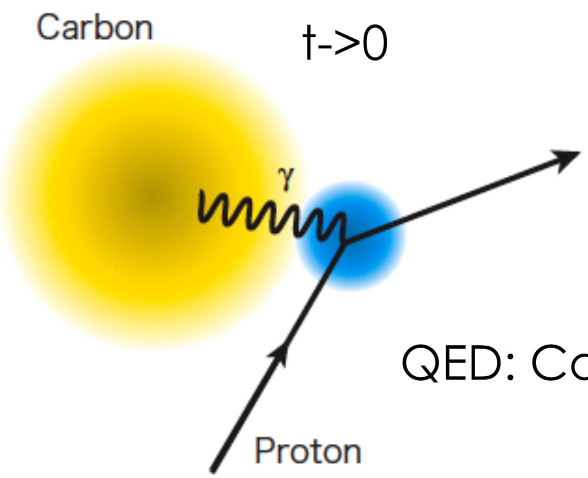


Elastic polarized proton-Carbon/proton scattering

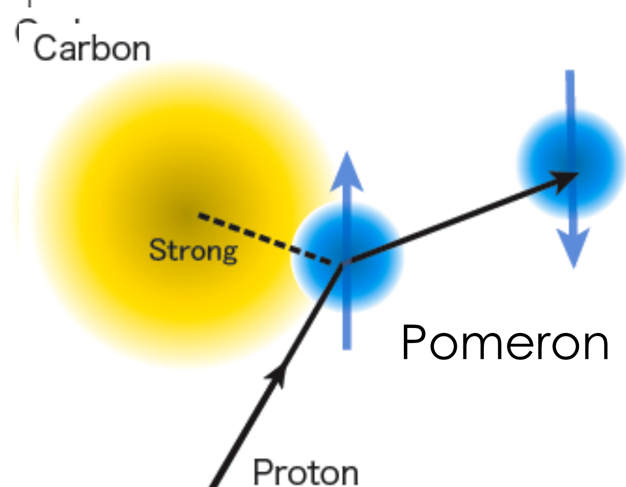
Analyzing Power A_N for polarimeter



Phys.Rev.Lett.,89,052302(2002)



QED: Calculable

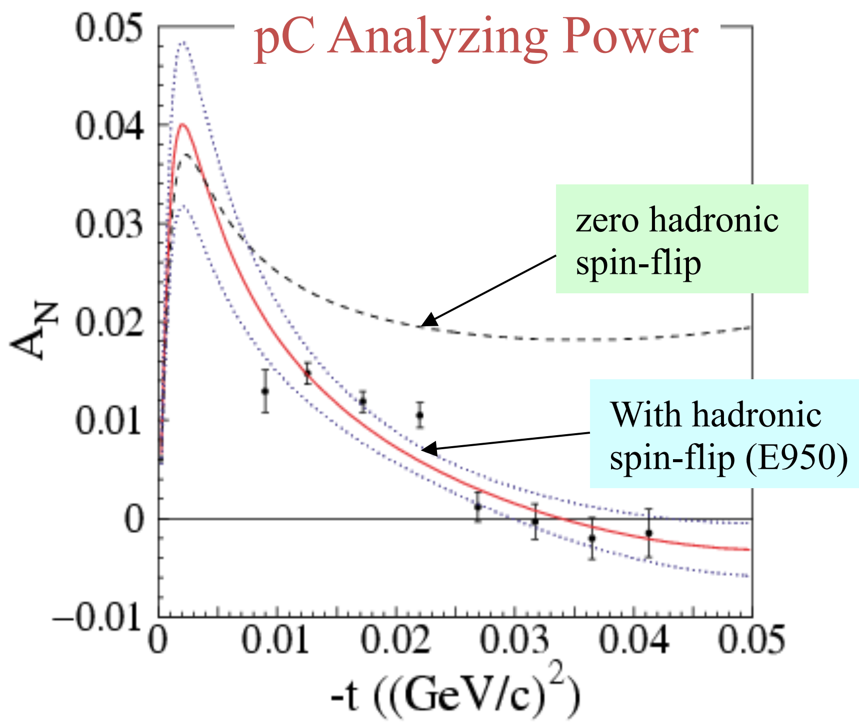


A_N at Coulomb Nuclear Interference (CNI) Region

$$A_N \approx C_1 \phi_{flip}^{em\,*} \phi_{non-flip}^{had} + C_2 \phi_{non-flip}^{em\,*} \phi_{flip}^{had}$$

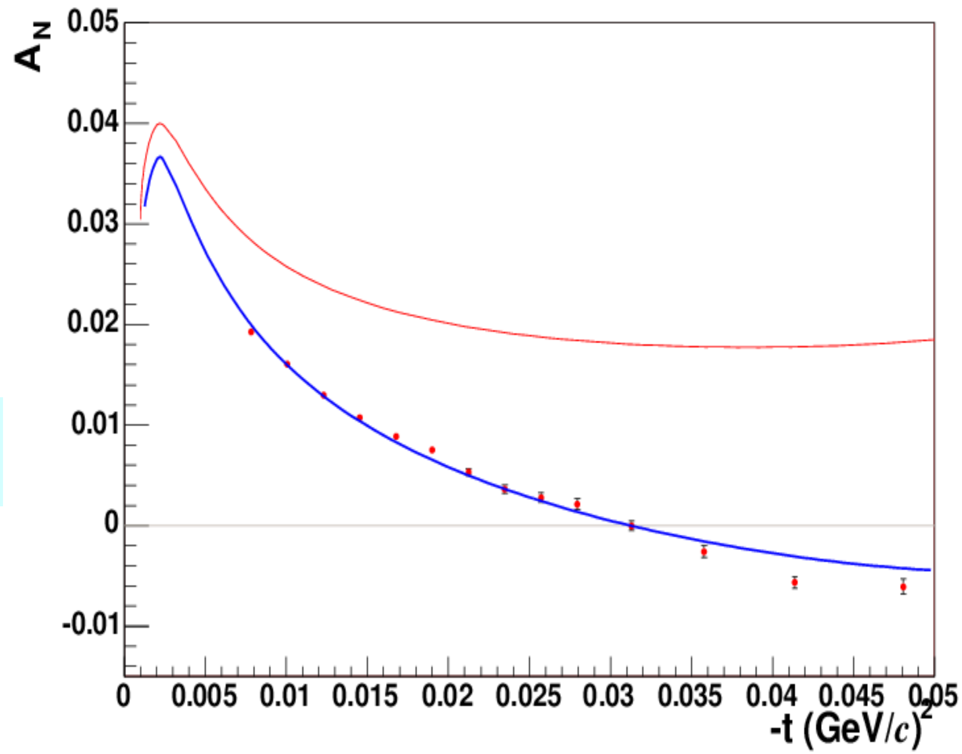
(High energy & small t limit) $\propto (\mu_p - 1)$ $\quad \propto \sqrt{\sigma_{pC}^{had}}$ $\quad \propto \alpha s / t$ $\quad$ Pomeron

Pomerion/Reggeon Exchange



Phys.Rev.Lett.,89,052302(2002)

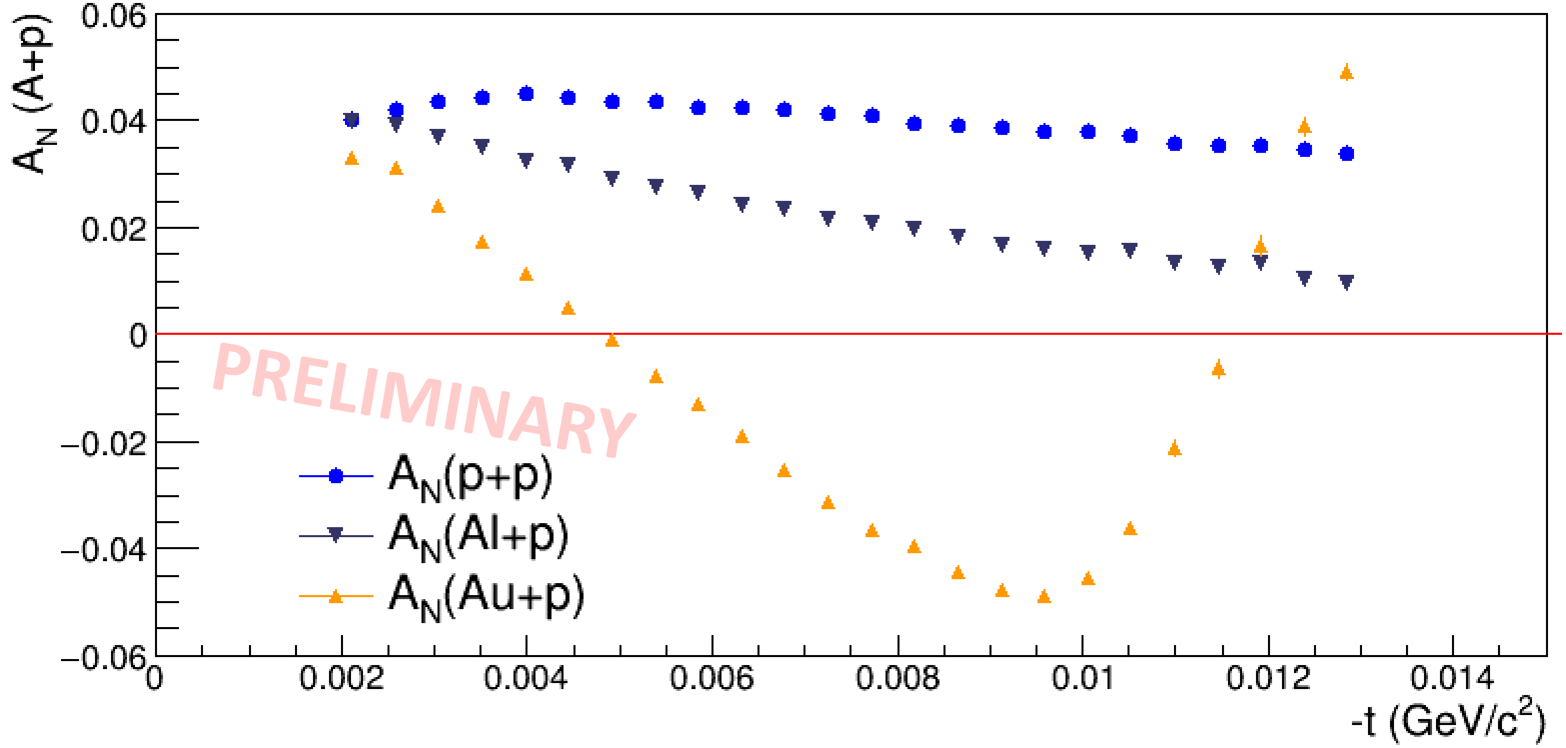
E_{beam} = 21.7GeV



unpublished

E_{beam} = 100 GeV

Analyzing Power: $A_N(\vec{p} + A)$



ZDC *t* range runs further out
t~0.02 - 0.5 (GeV/c) ^{2}
peaked at ~0.07 (GeV/c) ^{2}.

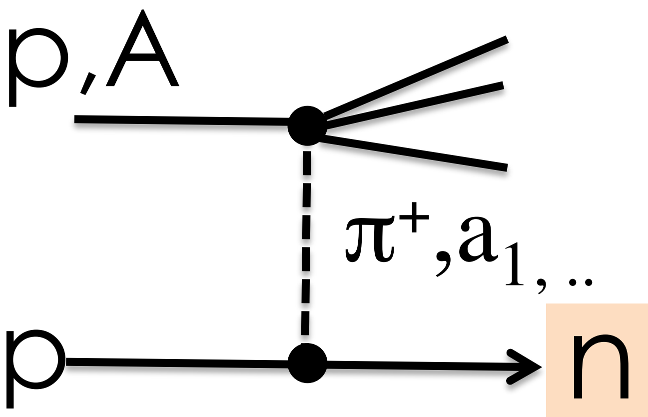
Run15 HJet results

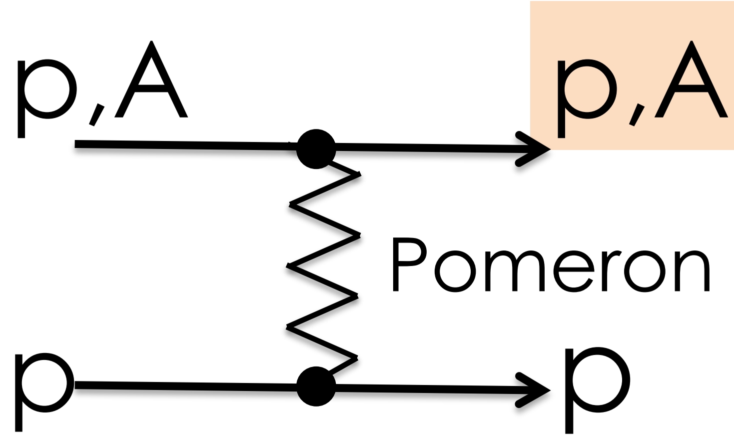
Slide from Oleg Eyser (The 2015 PSTP workshop)

Underlying Mechanism Comparison

Forward n

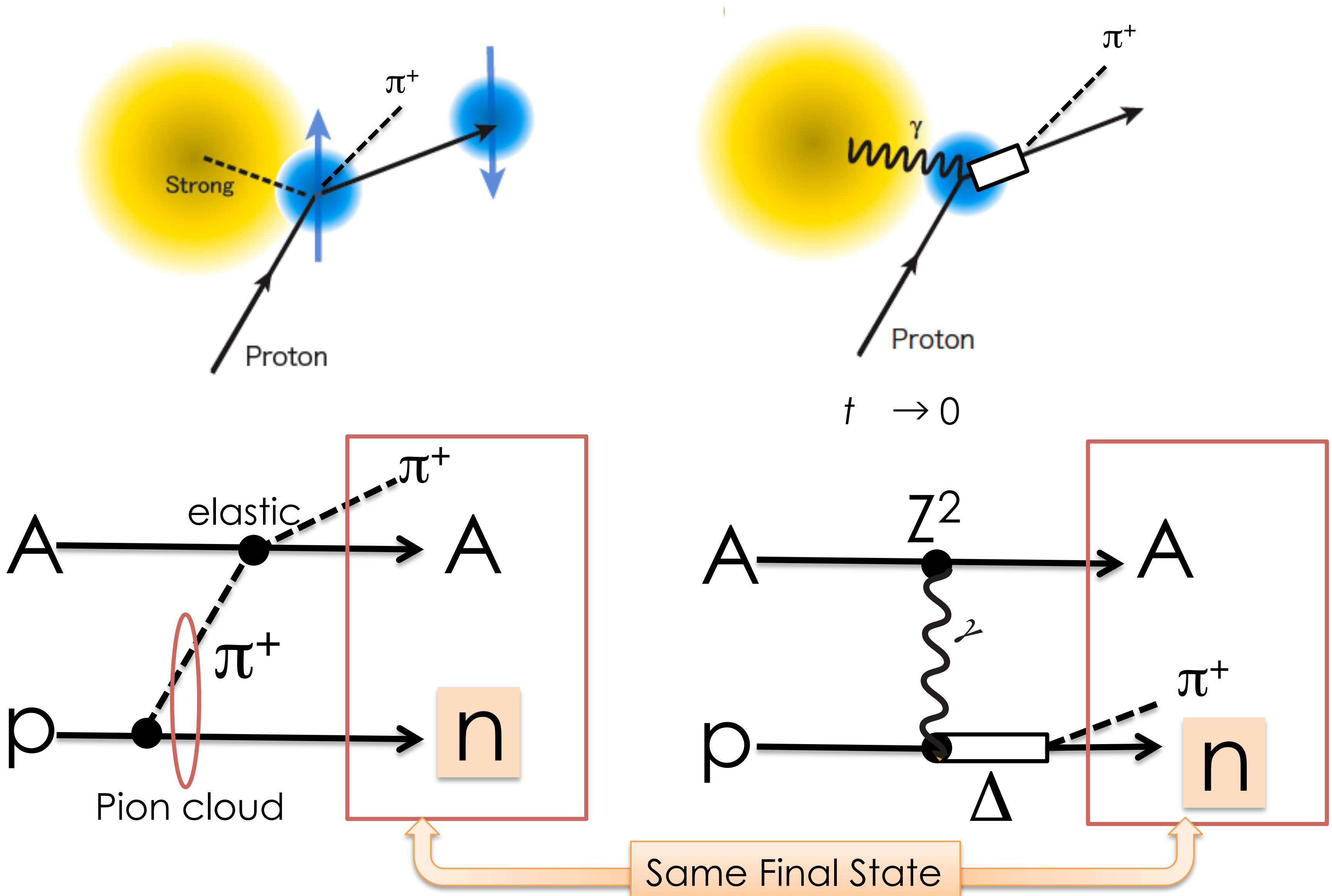
Polarimeter





$\Delta I = 1$	$\Delta I = 0$
Inelastic	Elastic
$\sqrt{s}$ = 200 GeV	$\sqrt{s}$ = 14 GeV

Coulomb-Nuclear Interference



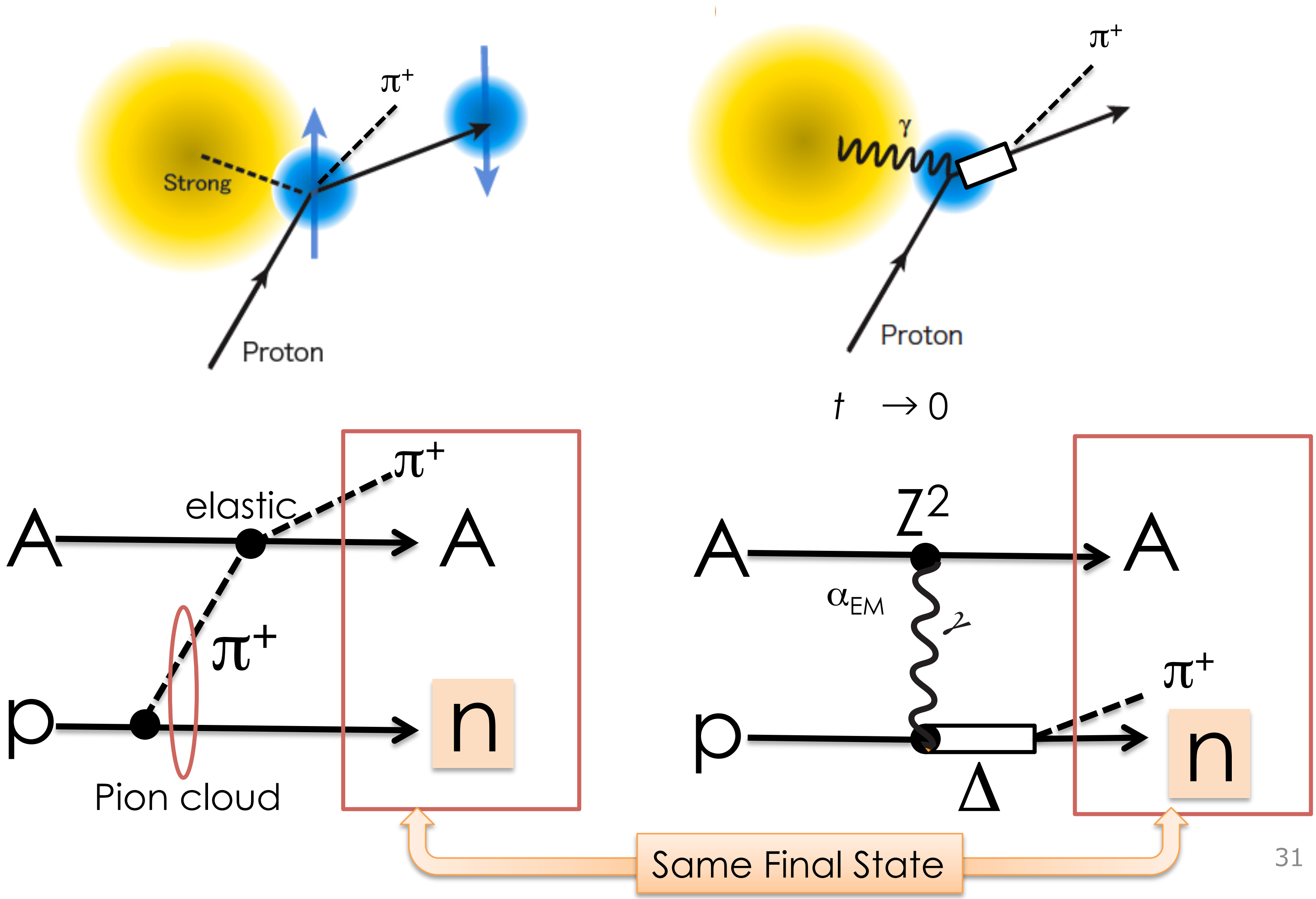
A_N at Coulomb Nuclear Interference (CNI) Region

$$A_N \approx C_1 \phi_{flip}^{em\,*} \phi_{non-flip}^{had} + C_2 \phi_{non-flip}^{em\,*} \phi_{flip}^{had}$$

(High energy & small t limit) $\propto (\mu_p - 1)$ $\propto \sqrt{\sigma_{pC}^{had}}$ $\propto \alpha s / t$ Pomeron Elastic pp/pA

	ϕ^{em}_{flip}	$\phi^{had}_{non\text{-}flip}$	$\phi^{em}_{non\text{-}flip}$	ϕ^{had}_{flip}
Elastic	$\propto (\mu_p - 1)$	$\propto \sqrt{\sigma_{pC}^{had}}$	$\propto \alpha s / t$	Pomeron
neutron	$\propto (\mu_p - 1) + \Delta$?	a_1	$\propto \alpha s / t + \Delta$?	π^+

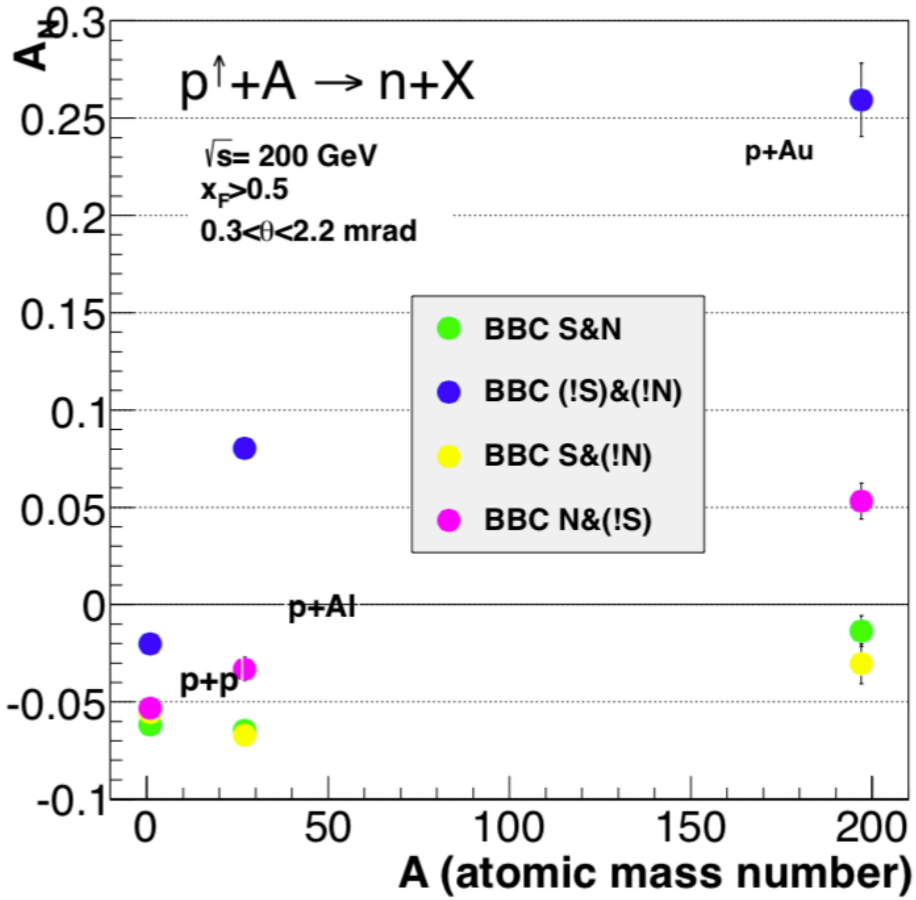
Coulomb-Nuclear Interfarence



CNI Summary

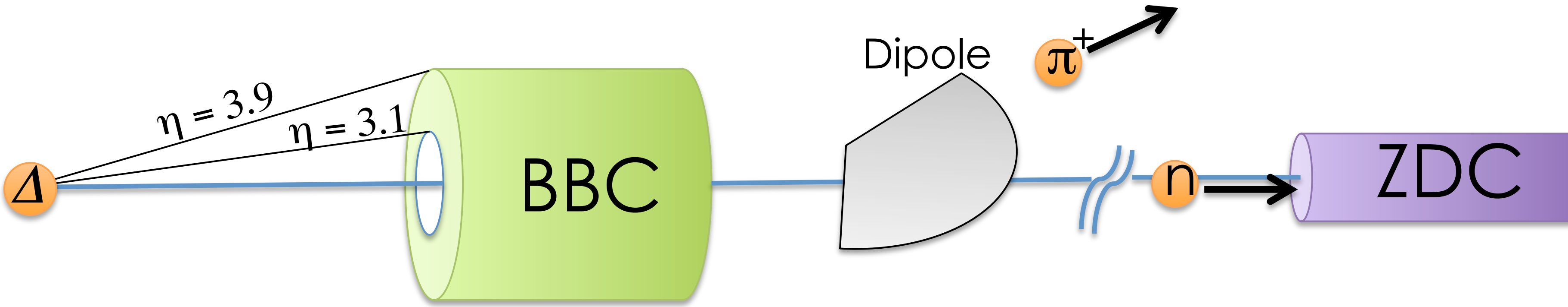
- The interference between QED process and strong force could open up possibility to larger asymmetry
- Similar behavior between CNI polarimeters may indicates the interference, but yet conclusive.

Trigger Dependent A_N



As soon as BBC is required, the A-Dependence becomes moderate.

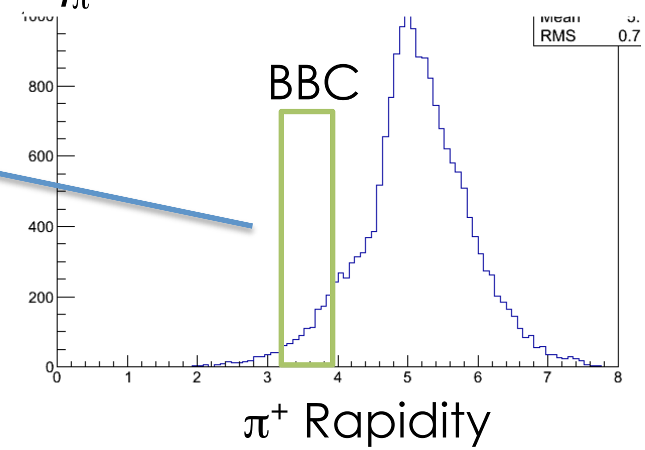
Can we identify UPC events?



BBC requires this minor pion to be detected

UPC (QED) contribution becomes small

η_π distribution of n+π^+ events



$$A_N = \phi_{flip}^{EM*}\phi_{non-flip}^{had}\delta + \phi_{flip}^{had*}\phi_{non=flip}^{EM}\delta + \phi_{flip}^{EM*}\phi_{non=flip}^{EM}\delta + \phi_{flip}^{had*}\phi_{non-flip}^{had}\delta$$

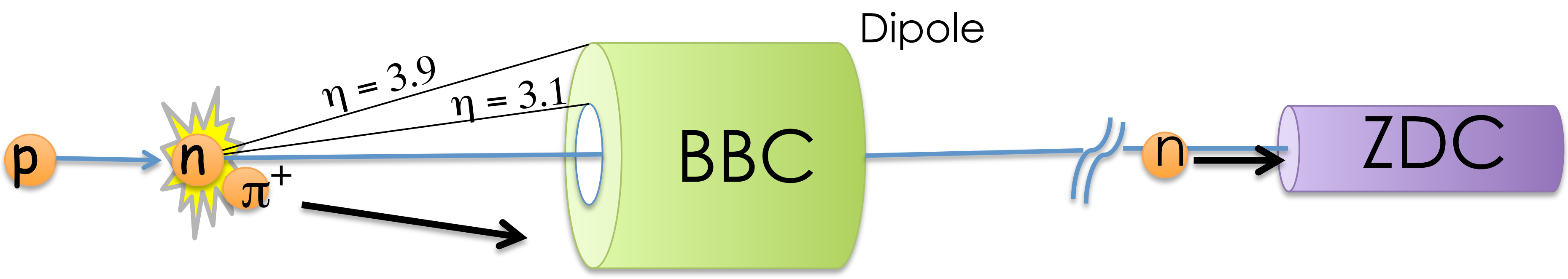
$$A_N \approx \phi_{flip}^{had*}\phi_{non-flip}^{had}\delta \quad \text{where} \quad \phi^{EM} \to 0$$

Trigger Dependence Summary

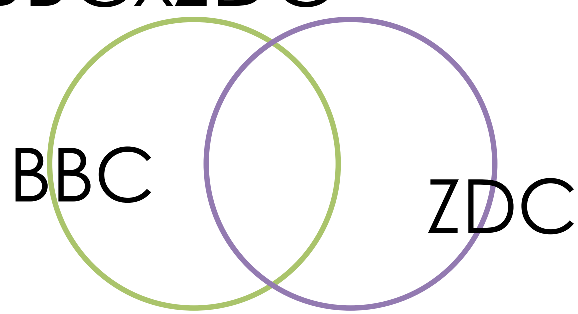
- ZDCxBBC suppresses UPC contribution
- Contribution from EM term becomes small.
- A_N is dominated by interference between strong force
- The difference in A_N between ZDC and ZDCxBBC should be rather substational in large A (Z) nuclei.

ZDCxBBC A_N and STAR pi0

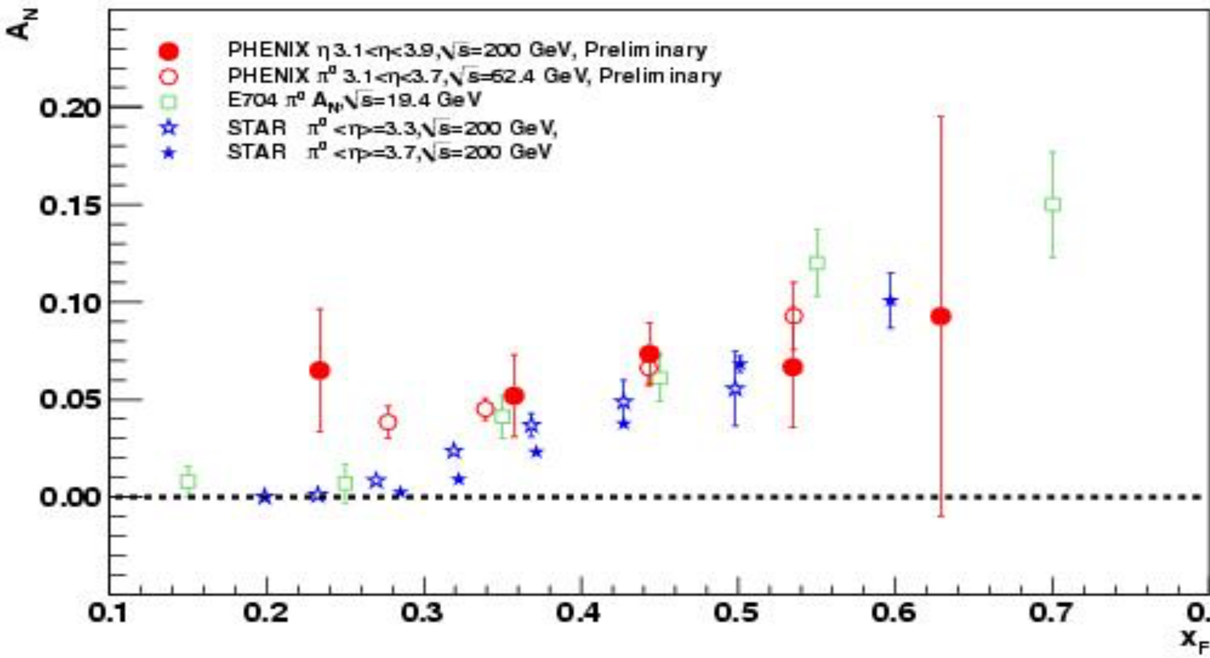
ZDC x BBC A_N



- The most simple final state will be $n+\pi^+$
- BBCxZDC is the subset of BBC inclusive event.
- It is possible to have finite A_N by only detecting π^+ in BBC. If inclusive BBC is dominated by $n+\pi^+$, then BBC A_N will be similar to BBCxZDC



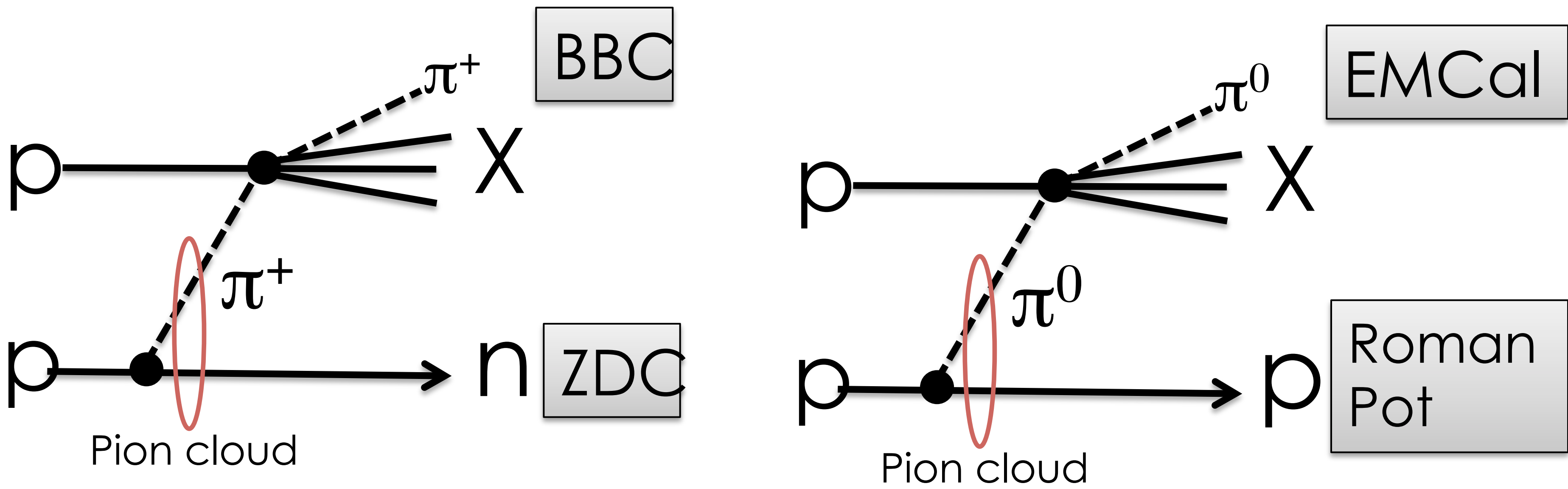
Forward π^0 A_N



- Another iso-spin alternative final state $p+\pi^0$ can be described in similar framework (assumption).
- MPC pi0 are similar rapidity with BBC.
- A_N gets larger at higher xF, but may be ~0.05 if statistically averaged becomes similar to BBCxZDC A_N

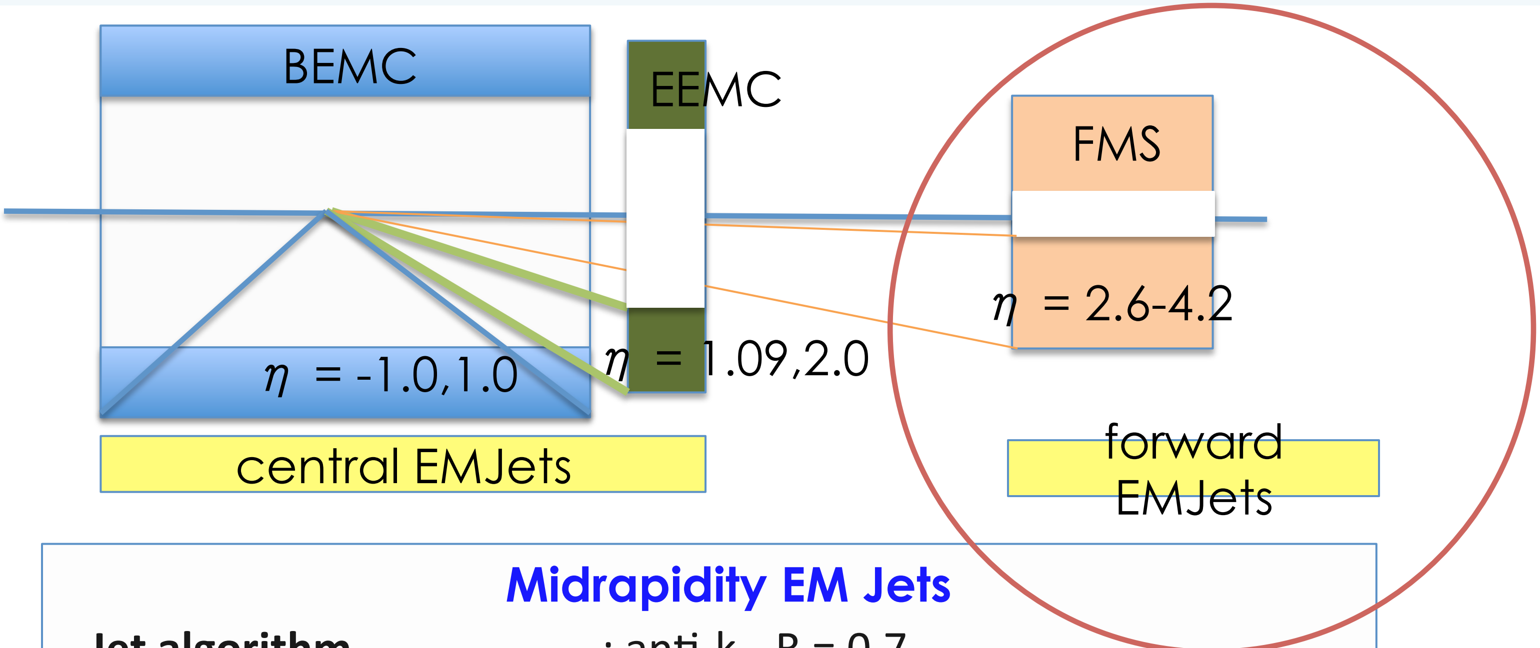
Diffractive process in pion cloud model

The proton ground state can be described as a super position of $n+\pi^+$ and $p+\pi^0$ states. I forgot relative strength between two states though.



Not sure if pi0 interfare with a1 reggion. May be different reggion.

STAR A_N



Midrapidity EM Jets

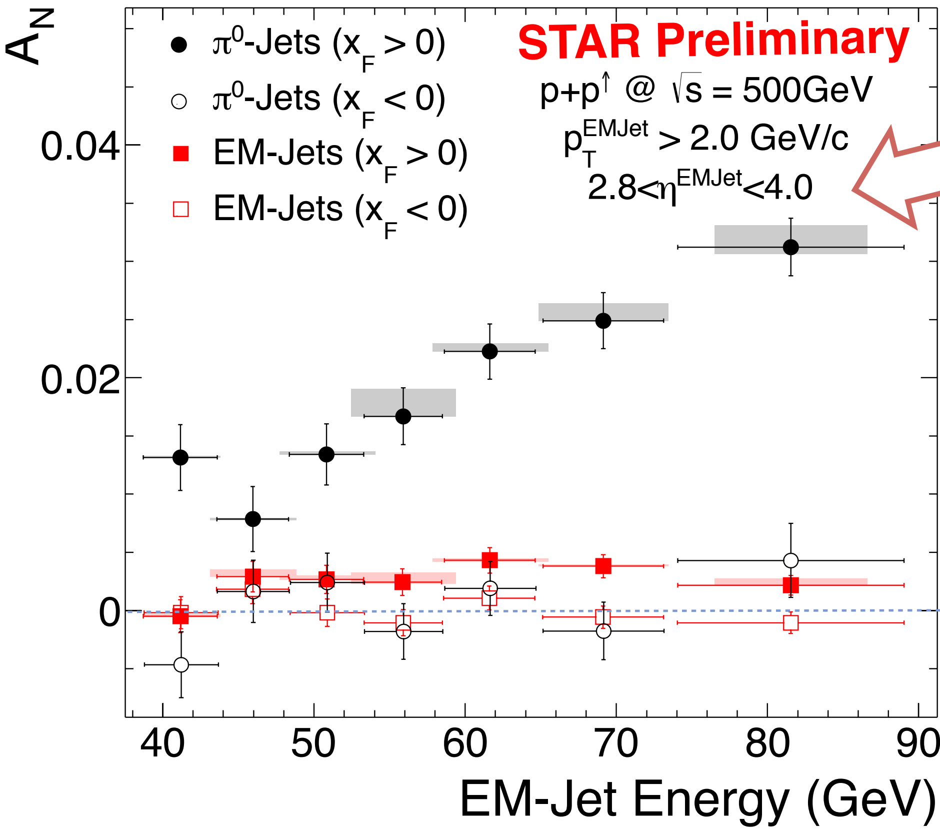
Jet algorithm : anti-k_T, R = 0.7
$p_T^{EM\text{-}Jet} > 2.0$ GeV/c, $-1.0<\eta^{EM\text{-}Jet}<2.0$

Inputs for central EMJets : towers from BEMC and EEMC

Leading central EM-Jets : Jet with highest p_T

- Case-I : having no central jet
- Case-II : having a central jet

A_N vs. EM-Jet Energy



Similar to BBC acceptance 3.1<eta<3.9

π^0-Jets –

2γ-EM-Jets with

$m_{\gamma\gamma}$ <0.3

$Z_{\gamma\gamma}$ <0.8

EM-Jets –

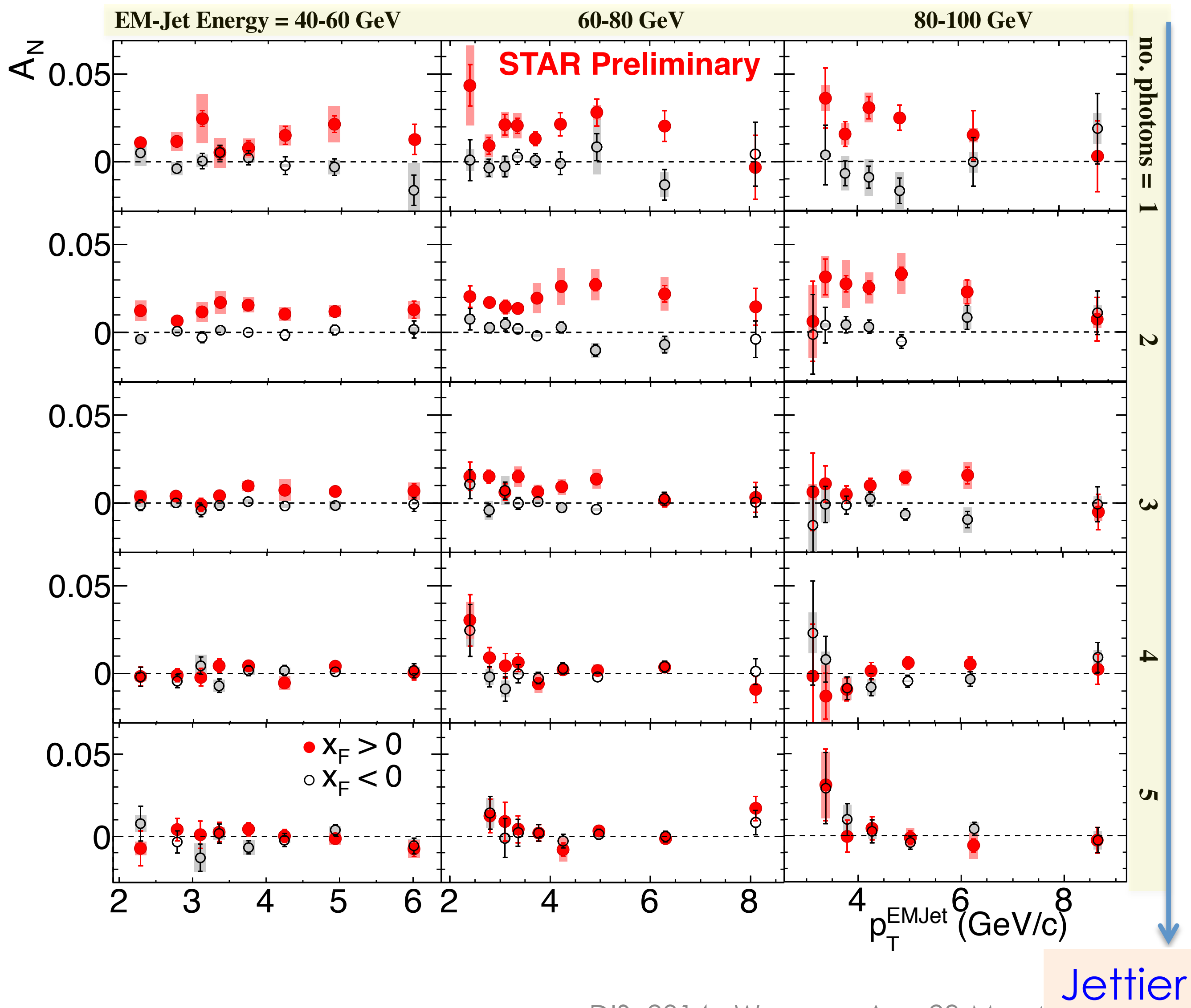
with no. photons >2

- ✧ Isolated π^0's have large asymmetries consistent with previous observation (CIPANP-2012 Steven Heppelmann)

https://indico.triumf.ca/contributionDisplay.pycontribId=349&sessionId=44&confId=1383

- ✧ **Asymmetries for jettier events are much smaller**

A_N for different # photons in EM-Jets



- ✧ 1-photon events, which include a large π^0 contribution in this analysis, are similar to 2-photon events
- ✧ Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated π^0's
- ✧ A_N decreases as the event complexity increases (i.e., the "jettiness"
- ✧ A_N for #photons >5 is similar to that for #photons = 5

STAR's Run15 Attempt

2015 Fall Meeting of the APS Division of Nuclear Physics

Volume 60, Number 13

Wednesday–Saturday, October 28–31, 2015; Santa Fe, New Mexico

Session DG: Mini-Symposium on the Spin Structure of the Nucleon II
10:30 AM–12:18 PM, Thursday, October 29, 2015
Room: Peralta

Chair: Fatiha Benmokhtar, Duquesne University

Abstract: DG.00003 : Dependence of Forward π^0 Transverse Single Spin Asymmetries on Roman Pot Triggers from $\sqrt{s} = 200$ GeV pp Collisions at STAR
10:54 AM–11:06 AM

Preview Abstract

MathJax ***On*** | *Off* ← *Abstract* →

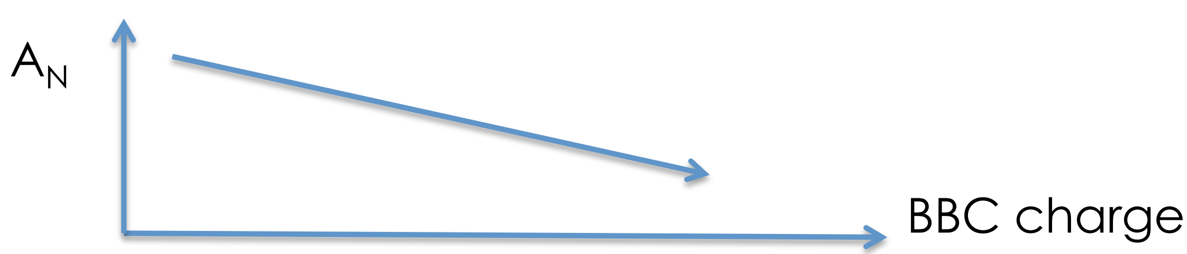
Author:
Christopher Dilks
(Pennsylvania State University)

Surprisingly substantial transverse single spin asymmetries, A_N, have been observed in many hadronic channels since 1976. Since then, many attempts have been made to explain the underlying mechanism, such as the Sivers effect, Collins effect, and twist-3 contributions; however, no explanation has been fully sufficient. Diffractive contributions to the cross-section may provide additional insight to the origin of the large A_N. In the most recent RHIC run of pp collisions, the Forward Meson Spectrometer, an electromagnetic calorimeter covering a forward pseudorapidity range of $2.6 < \eta < 4$, recorded a substantial data set mostly composed of π^0s from which A_N can be extracted. Furthermore, STAR installed Roman Pot silicon trackers to tag diffractive events through forward going protons. Correlations of π^0 events with Roman Pot triggers will for the first time address the role of the diffractive contributions to A_N. The status of the analysis of such correlations will be presented.

Trying to tag diffractive pi0 by taking coincidence with forward proton which stayed intact through collision.

Something similar to STAR Study

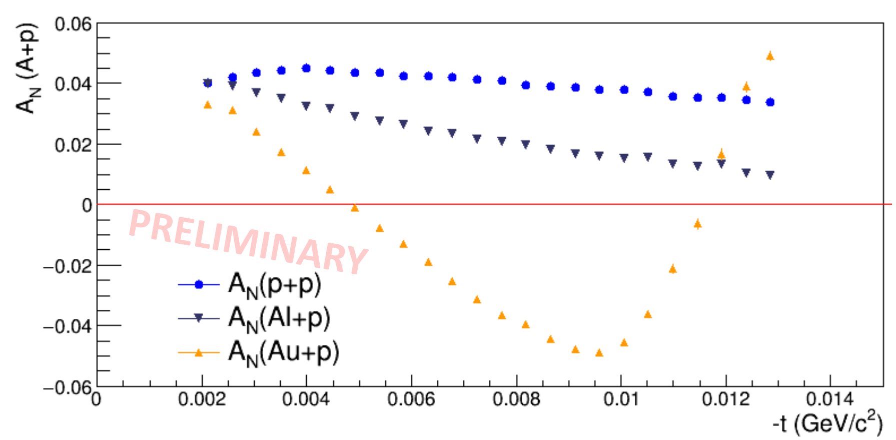
- See A_N dependence on BBC charge as Sasha suggested
- This more like seeing "diffractiveness". Smaller the BBC charge, the charged particle is isolated-> diffractive process.
- If this attempt is really similar to what STAR did, then the asymmetry will get smaller as BBC charge gets larger at least in pp.



Run16

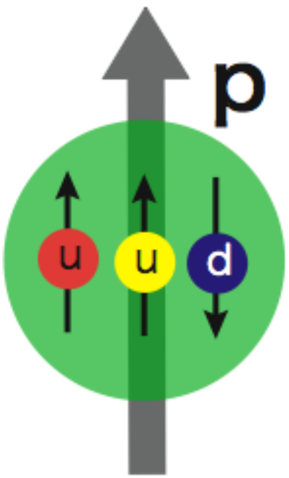
0.5 week	cool-down
1.5 week	setup for Au+Au @ 200 GeV
0.5 week	ramp-up
10 week	Au+Au @ 200 GeV
1 day	system and energy switchover
2 week	d+Au @ 20 GeV
0.5 week	setup for d+Au @ 39 GeV
2 weeks	d+Au @ 39 GeV
0.5 week	setup for d+Au @ 62 GeV
1.5 week	d+Au @ 62 GeV
0.5 week	setup for d+Au @ 200 GeV
1.5 week	d+Au @ 200 GeV
0.5 week	warm up
21.5 week	total cryo-weeks

- No pp
- No plan to run H-Jet due to lack of man power
- Need to estimate if 1.5 week is sufficient to accumulate statistics



BACKUP

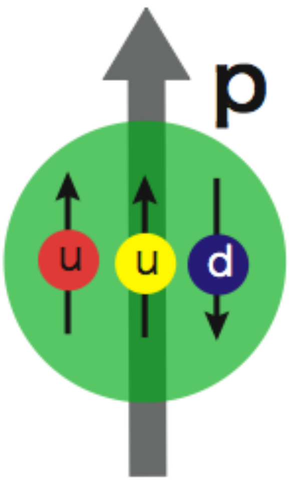
Proton Spin +1/2



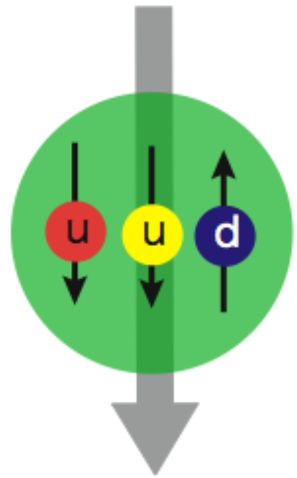
$$|p\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2}$$

Proton Spin +1/2



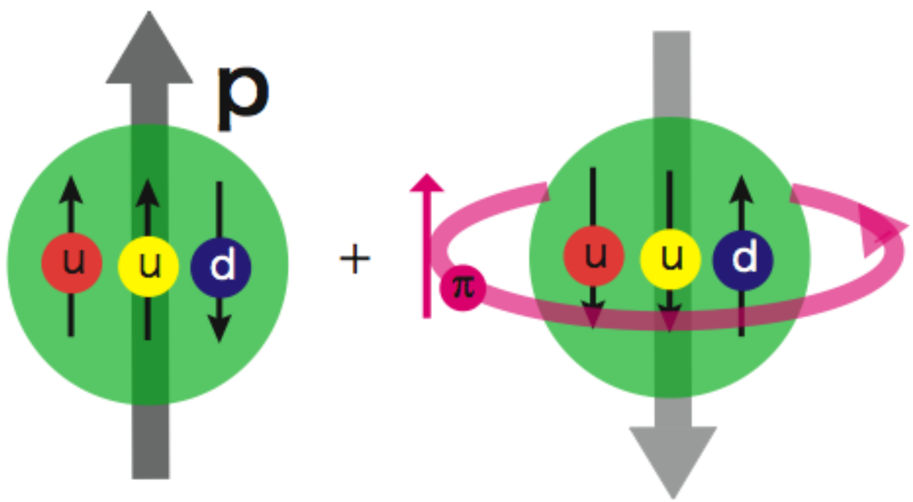
+



$$\left| p \right\rangle$$

$S + L = J$ $\qquad$ $+\frac{1}{2} + 0 = +\frac{1}{2}$ $\qquad$ $\left(-\frac{1}{2} + 0\right)$

Proton Spin +1/2

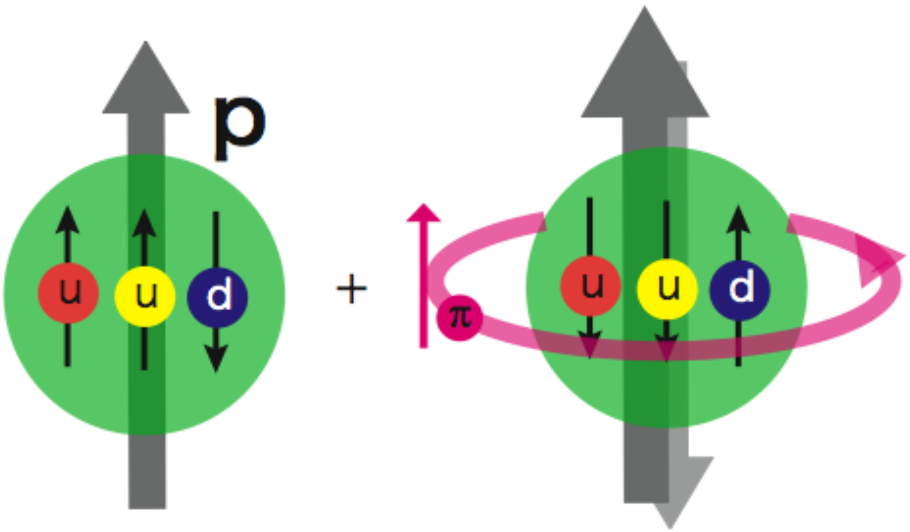


$$|p\rangle \qquad |N\pi\rangle$$

$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) =$

P-wave

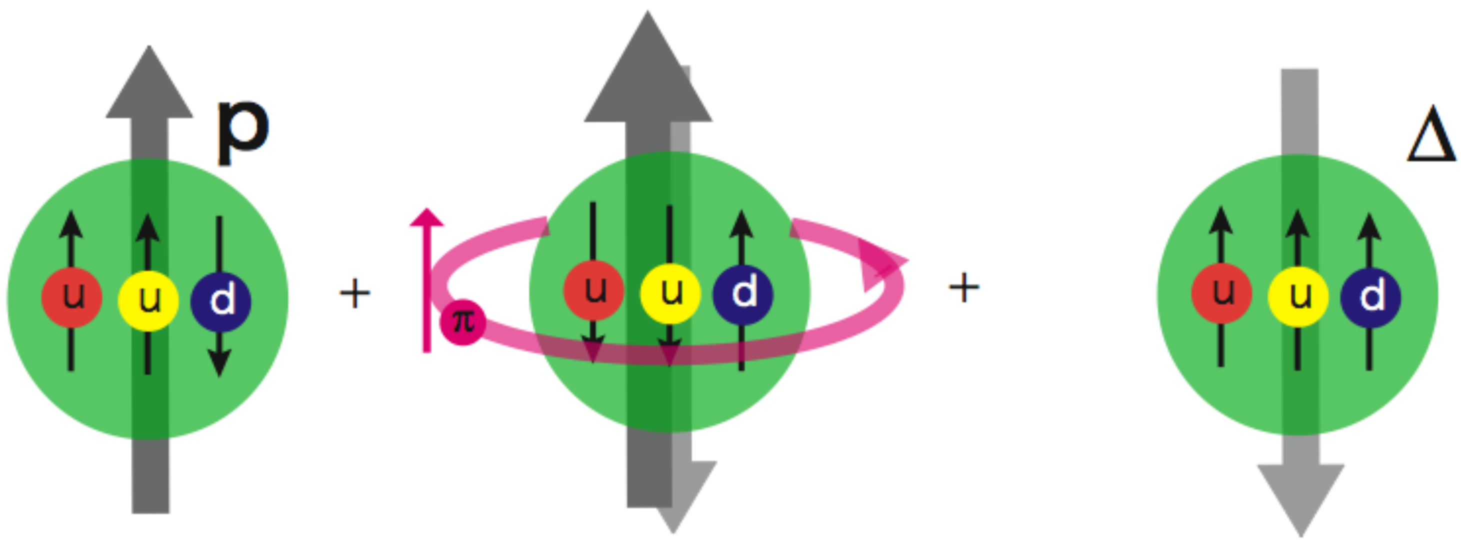
Proton Spin +1/2



$$|p\rangle \qquad |N\pi\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) = +\frac{1}{2}$$

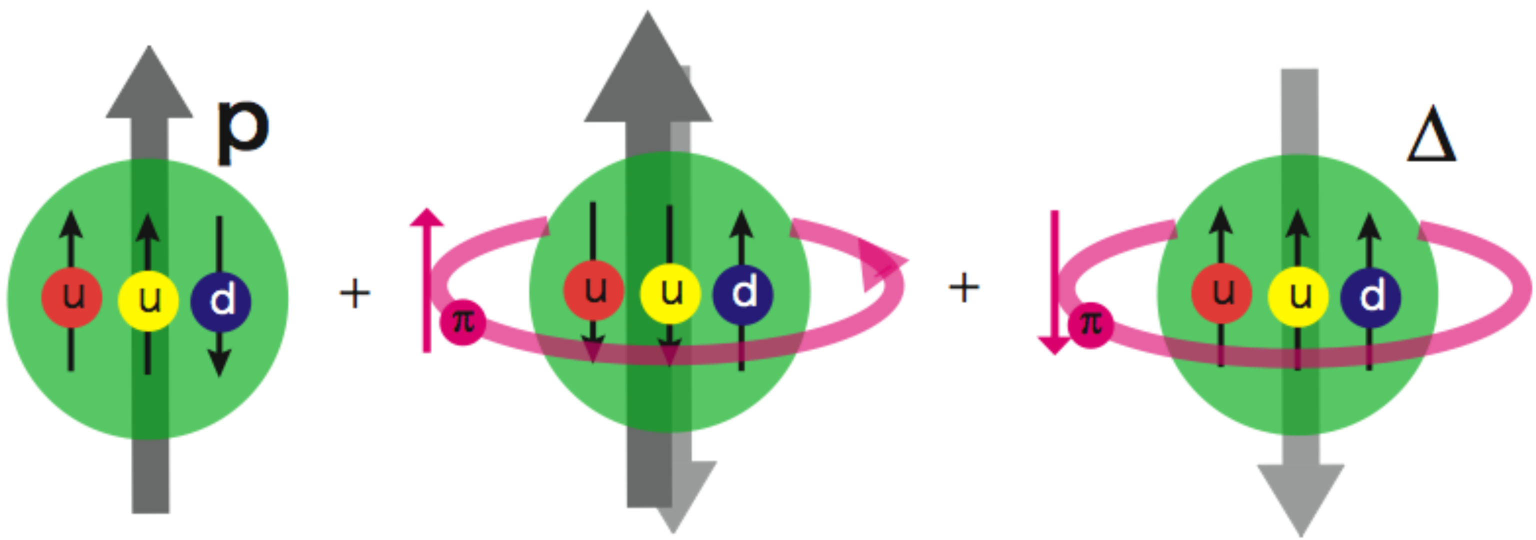
Proton Spin +1/2



$$|p\rangle \qquad\qquad |N\pi\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) = +\frac{1}{2} \qquad \left(\frac{3}{2} + 0\right)$$

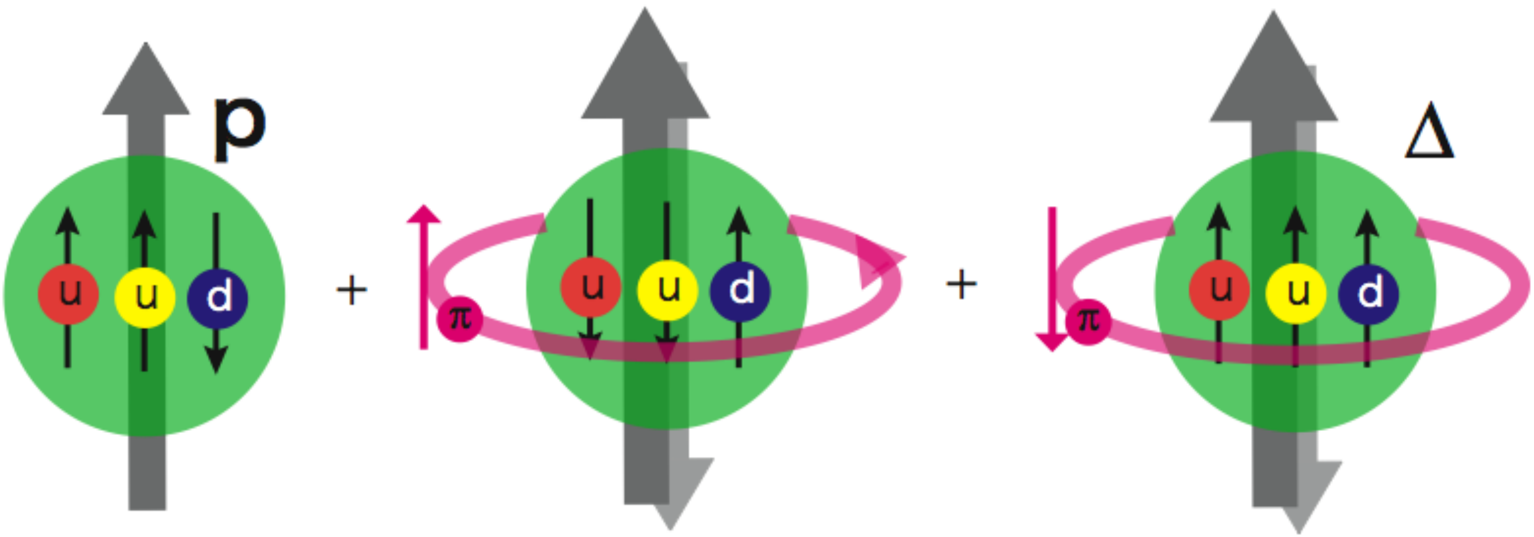
Proton Spin +1/2



$$|p\rangle \qquad |N\pi\rangle \qquad |\Delta\pi\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) = +\frac{1}{2} \qquad \left(\frac{3}{2} + 0\right) + (0 - 1) =$$

Proton Spin +1/2



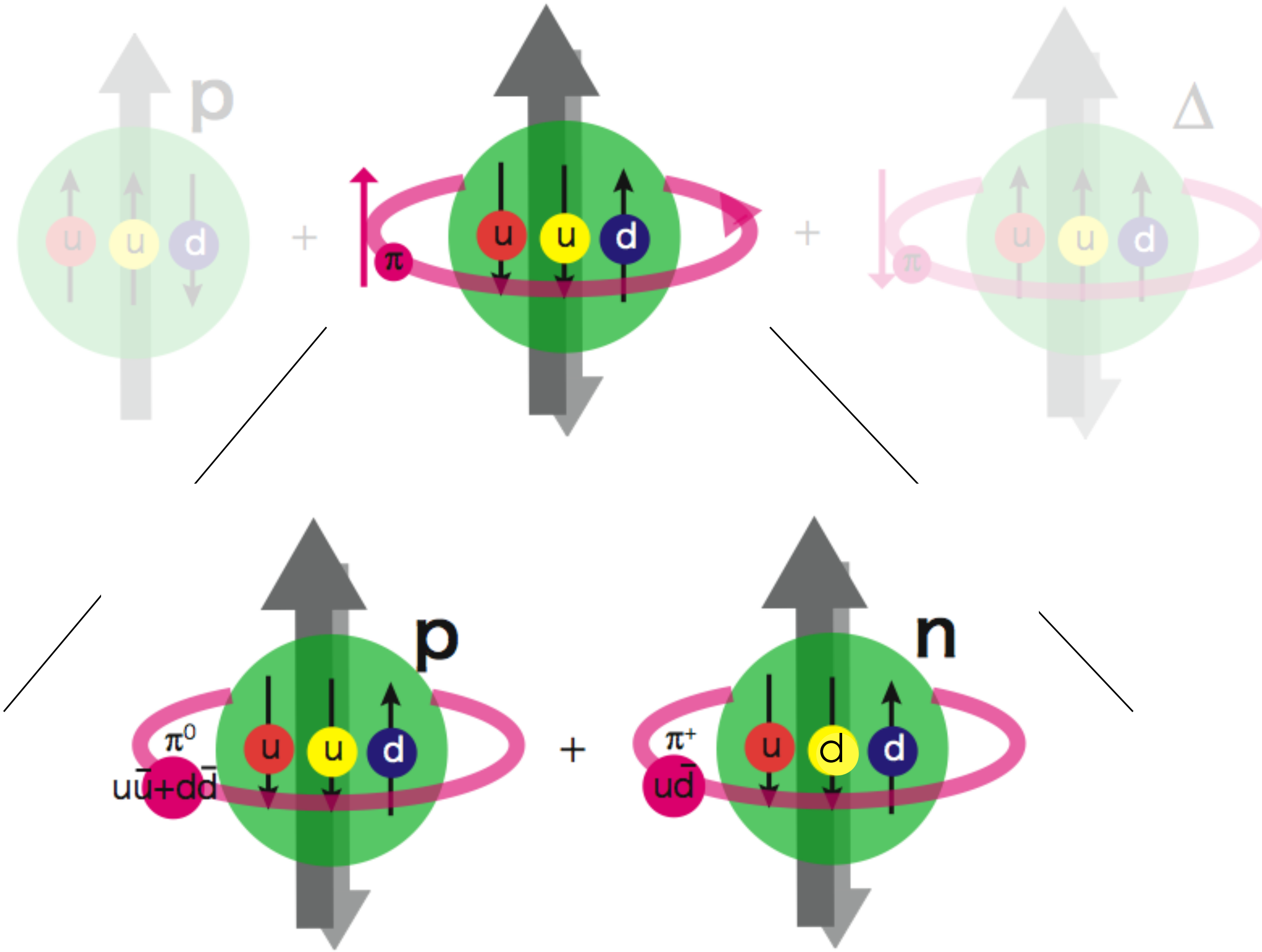
$$|p\rangle \qquad |N\pi\rangle \qquad |\Delta\pi\rangle$$

$$S + L = J \qquad +\frac{1}{2} + 0 = +\frac{1}{2} \qquad \left(-\frac{1}{2} + 0\right) + (0 + 1) = +\frac{1}{2} \qquad \left(\frac{3}{2} + 0\right) + (0 - 1) = +\frac{1}{2}$$

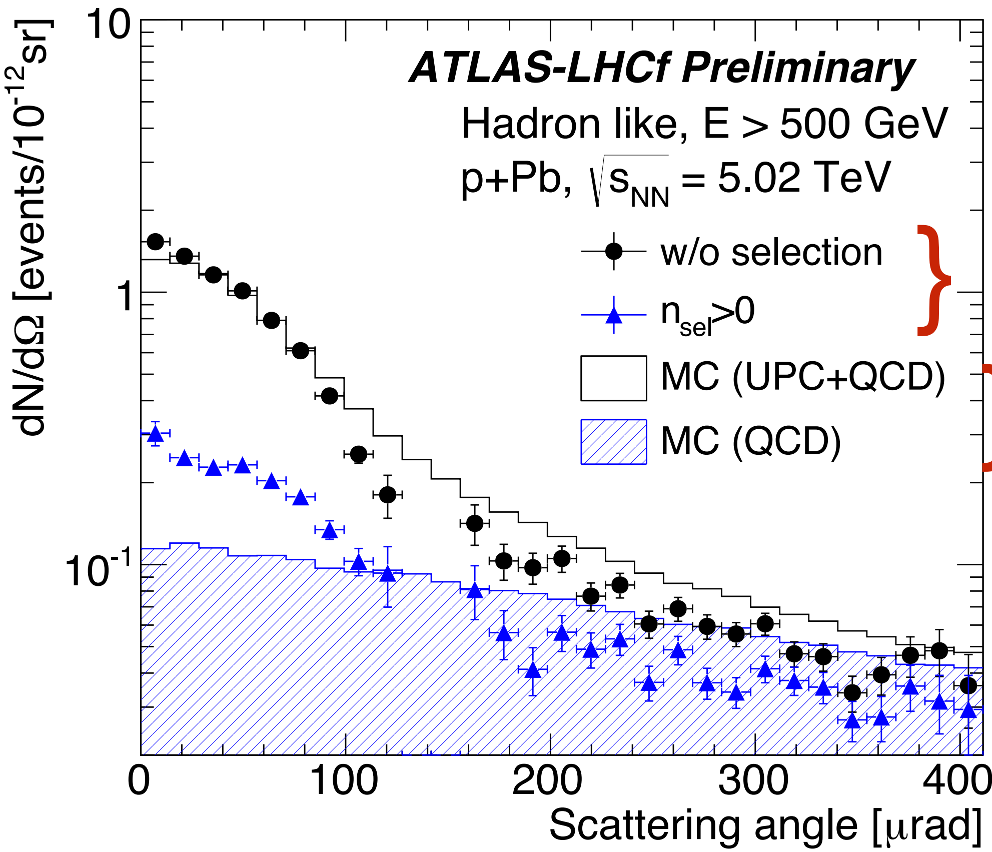
P-wave

P-wave

Proton Spin +1/2



Hit Map of Hadron like events



Note) The sum of UPC and QCD simulations was normalized to all data in the range from 0 μrad to 120 μrad.

Data with the event selection by number of tracks in ATLAS; n_{sel}

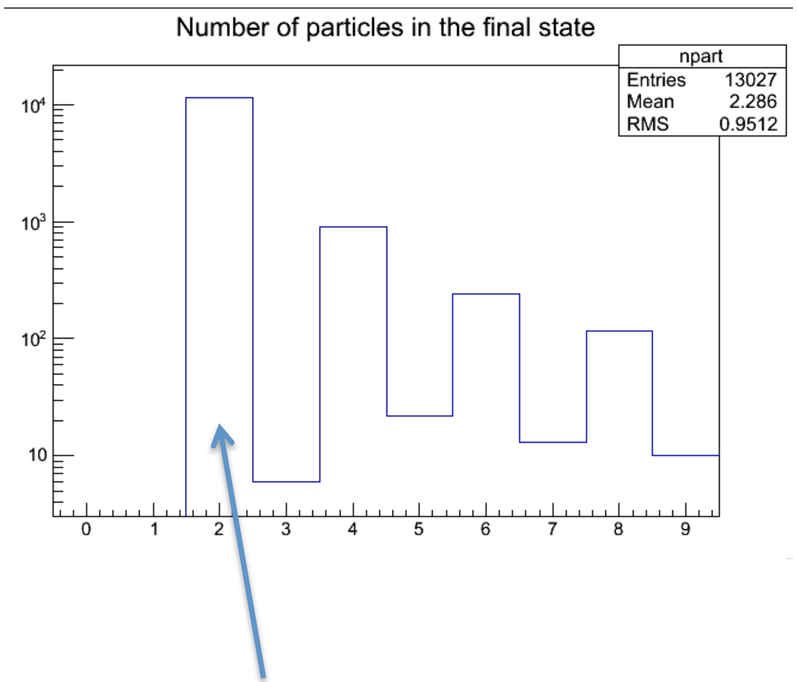
MC with the selection by process

✓ Clear concentration at zero degree with events of n_{sel}=0.

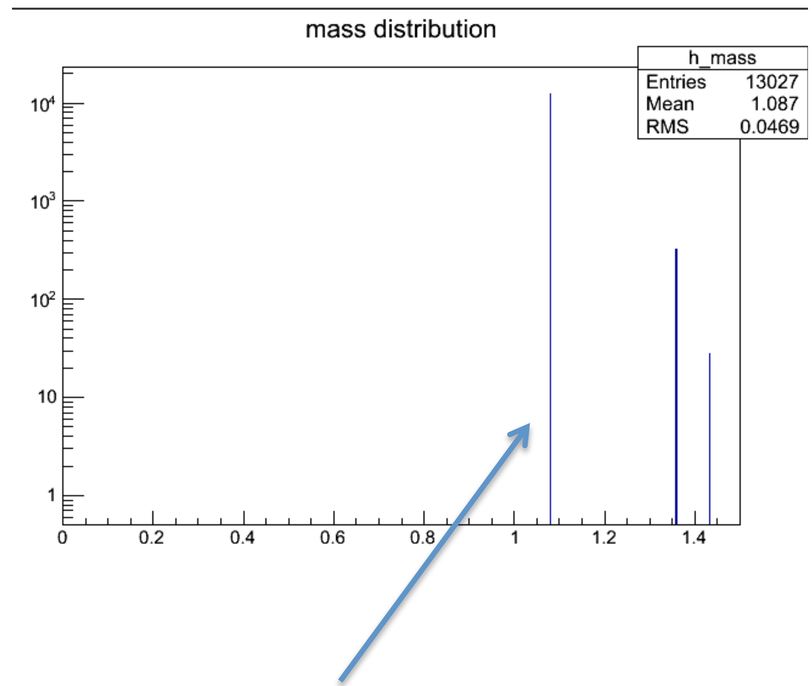
✓ Similar distribution of n_{sel}>0 as one of MC (QCD)

- Confirmed that the trigger exchange in 2013 operation was correctly done.
- The joint analysis clearly helps to study the forward particle production with categorizing the type of interaction.

UPC Final States for forward neutron in ZDC

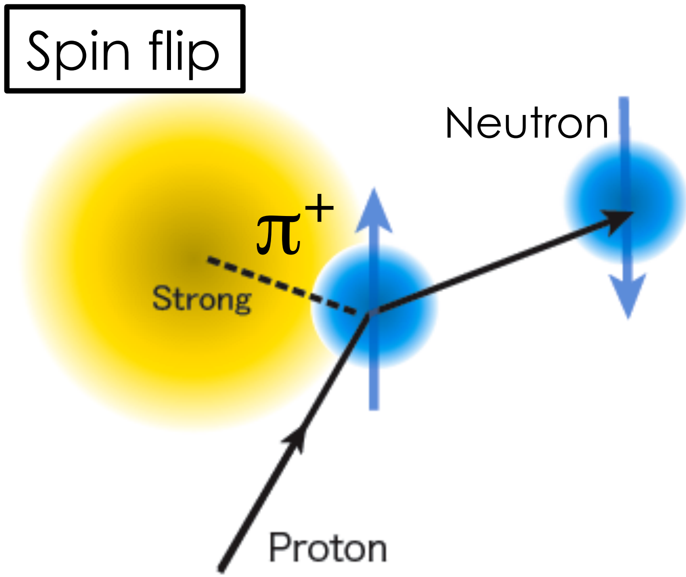


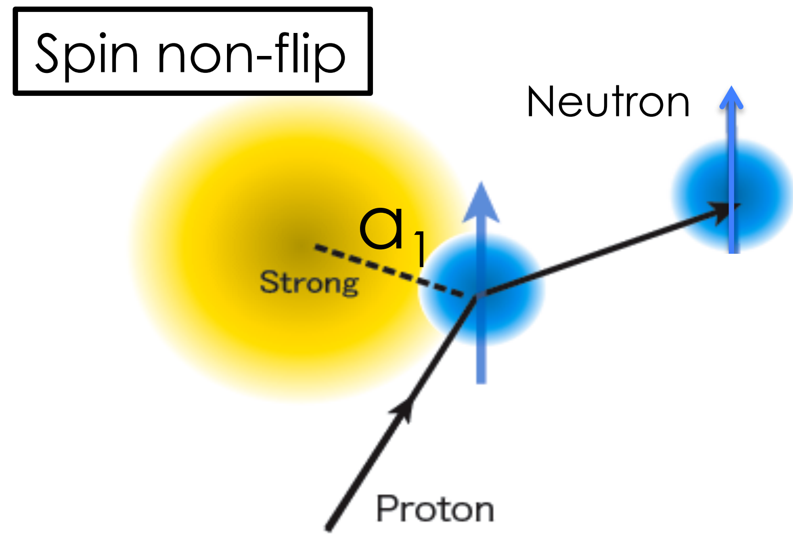
Dominated by two body decay



Dominated by neutron + π^+ system

$p^{\uparrow}p$ Forward Neutron A_N





$$A_N \approx \frac{\phi^*_{non-flip}\phi_{flip}\delta}{\left|\phi_{non-flip}\right|^2 + \left|\phi_{flip}\right|^2} \approx \frac{\phi^*_{non-flip}\phi_{flip}\delta}{\sigma_{OPE}}$$

$\phi^{a_1}_{non-flip} << \phi^{\pi}_{flip}$

OPE : One Pion Exchange